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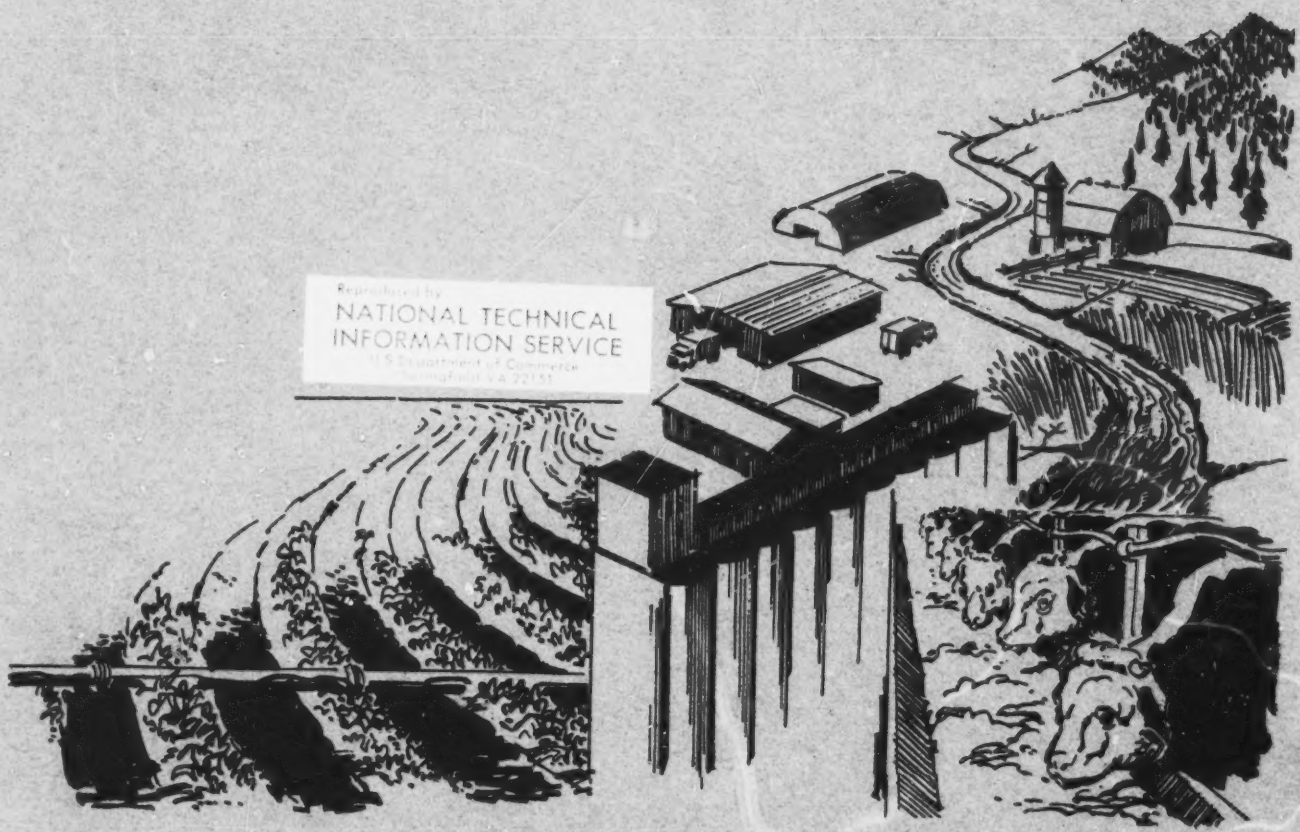

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CLOSED SYSTEM WASTE MANAGEMENT FOR LIVESTOCK

Ngoddy, P. O. Harper, J. O.
Collins, R.K., Wells, G. D. Heidar, F. A.

Michigan State University, East Lansing, ~~Michigan~~ Department of Agricultural Engineering

Environmental Protection Agency

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A vibrating screen separator has been developed for liquid-solid separation of livestock wastewater. Pilot tests on swine and beef cattle wastewater have shown that the resistant or slowly biodegradable solids are effectively removed on vibrating screens ranging in mesh size from #60 to #120. Although measurably less efficient than conventional dewatering devices such as centrifuges and vacuum filters, the gravity dewatering vibrating screen separation is better suited to the economic scale of the average livestock operation. The removal of resistant solids from wastewater prior to stabilization substantially improves the performance of biological treatment systems by enhancing the controlling transport and kinetic mechanisms in such processes. Screened solids are odorless, stable, and storable over long periods without an odor nuisance or pollutional problem. The liquid fraction can be partially reclaimed by biodegradation and recycled as transport water. A number of candidate livestock waste management designs integrating the salient features of the study have been proposed. (Lowry-Texas)

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CLOSED SYSTEM WASTE MANAGEMENT FOR LIVESTOCK

by

Dr. Patrick O. Ngoddy, Assistant Professor
Principal Investigator

Jerome P. Harper, Chemical Analyst

Robert K. Collins, Engineering Technician

Grant D. Wells, Graduate Research Assistant

Farouk A. Heidar, Graduate Research Assistant

Agricultural Pollution Control Laboratory
Department of Agricultural Engineering
Michigan State University
East Lansing, Michigan 48823

for the

OFFICE OF RESEARCH AND MONITORING

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ABSTRACT

The vibrating screen separator is examined for liquid-solid separation of livestock wastewater. A general procedure for performance analysis and estimation of this type of dewatering apparatus is developed and verified using methods of dimensional analysis. Tests on swine and beef cattle wastewaters show that the resistant or slowly biodegradable solids are effectively removed on vibrating screens ranging in mesh size from #60 to #120. Although it is measurably less efficient than conventional dewatering devices such as centrifuges and vacuum filters, the gravity dewatering screen separator is better suited to the economic scale of the average livestock operation.

The separated solid fraction from the screen is fibrous, odor free, stable, storable and does not attract flies. The absence of these solids from the liquid fraction is shown to stimulate faster rates of COD and nuisance odor dissipation presumably by enhancing otherwise rate-limiting transport processes in biological treatment systems.

The salient aspects of this study are integrated into candidate confinement livestock waste management designs featuring

(i) the hydraulic transport of wastes with treated recycled wastewater

(ii) ultimate disposal of separated liquid and solid fractions without pollution or nuisance odor problem.

This report was submitted in fulfillment of Project Number 13040 DKP under the(partial)sponsorship of the Office of Research and Monitoring, Environmental Protection Agency.

CONTENTS

Section		Page
I	Conclusions	1
II	Recommendations	3
III	Introduction	5
IV	Production Rates and Pollutional Characterization of Hog and Beef Cattle Manures	9
V	Solid-Liquid Separation Studies	21
VI	Characteristics of the Component Liquid and Solid Fractions of Beef Cattle and Swine Wastewaters	65
VII	Comparative Biological Treatability Studies on Swine and Beef Cattle Wastewater Liquid Fractions	77
VIII	Design Alternatives	95
IX	Acknowledgements	107
X	References	109

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FIGURES

		PAGE
1	METABOLISM CAGES FOR SWINE WASTE COLLECTION	10
2	METABOLISM CAGES FOR BEEF CATTLE WASTE COLLECTION	11
3	VERTICAL SECTION THROUGH A BASIC SINGLE DECK, 18" SWECO VIBRATING SCREEN SEPARATOR	24
4	ILLUSTRATION OF AVERAGE MATERIAL TRAVEL ON SCREEN	25
5	OPTIMIZATION PLOT FOR SWINE WASTEWATER	31
6	PERFORMANCE CURVES FOR SWINE WASTEWATER	32
7	AVERAGE PERCENTAGE REMOVAL VS. MESH SIZE OF SCREEN PLOTTED ON LOG-PROBABILITY PAPER	37
8	SCHEMATIC OF EXPERIMENTAL APPARATUS FOR VIBRATING SCREEN TESTS	40
9	CLOSE-UP VIEW OF SETUP FOR SCREEN TEST	41
10	ALTERNATIVE PLOTS OF THE SCREEN TEST DATA ON SWINE WASTEWATER	51
11	PERFORMANCE CURVES FOR SWINE WASTEWATER	56
12	OPTIMIZATION PLOTS FOR BEEF CATTLE WASTEWATER	57
13	SCREEN PERFORMANCE CURVE FOR BEEF CATTLE WASTEWATER	58
14	DIAGRAMATIC SECTION THROUGH EXPERIMENTAL SAND FILTER	60
15	CLOSE-UP VIEW OF SETUP FOR SAND FILTER TEST	61
16	CLOSE-UP VIEW OF EXPERIMENTAL COMPOST SETUP	74
17	TEMPERATURE PROFILE OF COMPOST BEDS	75
18	CLOSE-UP VIEW OF ANAEROBIC DIGESTERS	78
19	DETAIL OF ANAEROBIC DIGESTER	79
20	ANAEROBIC DIGESTER PERFORMANCE PLOTS	84
21	VOLATILE SOLIDS DISSIPATION FOR SWINE WASTEWATER ANAEROBICALLY DIGESTED AT 95°F	85

22	VOLATILE SOLIDS DISSIPATION FOR BEEF CATTLE WASTE-WATER ANAEROBICALLY DIGESTED AT 95°F	86
23	CLOSE-UP VIEW OF BIOXIDATION APPARATUS	87
24	BIOXIDATION OF SWINE WASTEWATER LIQUID FRACTION, COD REMOVAL RATE PLOT	90
25	BIOXIDATION OF BEEF CATTLE WASTEWATER LIQUID FRACTION, COD REMOVAL RATE PLOT	92
26	LAYOUT OF PROPOSED WASTE MANAGEMENT SYSTEM	96
27	PROPOSED CLOSED SYSTEM WASTE MANAGEMENT FOR LIVESTOCK	97
28	LAGOON SECTION -- DETAILS	99

TABLES

		PAGE
1	ANIMAL WASTE CHARACTERISTICS IN TERMS OF 1000 LB. LIVE WEIGHT	13
2	SWINE INPUT-OUTPUT SUMMARY	14
3	SWINE FEED MIX	15
4	POLLUTIONAL CHARACTERISTICS OF SWINE WASTE	16
5	MINERAL ANALYSIS -- (FEED, FECES, URINE) SWINE	17
6	FEEDER CATTLE INPUT-OUTPUT SUMMARY	18
7	MINERAL ANALYSIS -- BEEF CATTLE WASTE	19
8	VARIABLES AFFECTING THE PERFORMANCE OF VIBRATING SCREEN SEPARATOR	27
9	SIEVE ANALYSIS AND THE REMOVAL PERCENTAGE ESTIMATES OF SWINE WASTEWATER SOLIDS	35
10	SIEVE ANALYSIS OF BEEF CATTLE WASTEWATER SOAKING TIME 24 HOURS, APPROXIMATELY 5% TS	35
11	VALUES OF $A = (\frac{C_f - C_c}{C_f} \times 100) \frac{D_p}{D_s}$ AS USED IN THIS STUDY	39
12a	RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON SWINE WASTEWATER #50 Mesh Screen	43
12b	RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON SWINE WASTEWATER #74 Mesh Screen	44
12c	RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON SWINE WASTEWATER #120 Mesh Screen	45
12d	RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON SWINE WASTEWATER #200 Mesh Screen	46
12e	RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON SWINE WASTEWATER #230 Mesh Screen	47
13a	RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON BEEF CATTLE WASTEWATER #74 Mesh Screen	48
13b	RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON BEEF CATTLE WASTEWATER #74 Mesh Screen	49

13c	RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON BEEF CATTLE WASTEWATER #120 Mesh Screen	49
13d	RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON BEEF CATTLE WASTEWATER #50 Mesh Screen	50
14	SAND FILTER STUDY -- SWINE WASTEWATER	62
15	SUMMARY SHEET CHARACTERISTICS OF THE SOLID FRACTION (SWINE AND BEEF CATTLE WASTEWATER)	66
16a	SWINE WASTEWATER SCREENED	67
16b	NUTRIENT AND MINERAL ANALYSIS OF SWINE WASTEWATER SOLID & LIQUID FRACTIONS	68
16c	BIOLOGICAL OXYGEN DEMAND -- SWINE (80% URINE + 20% FECES) (NO DILUTION)	69
17a	BEEF CATTLE WASTEWATER SCREENED	70
17b	NUTRIENT AND MINERAL ANALYSIS OF BEEF CATTLE WASTEWATER LIQUID & SOLID FRACTIONS	71
17c	BIOLOGICAL OXYGEN DEMAND -- BEEF CATTLE (60% FECES + 40% URINE) (NO DILUTION)	72
18	ANAEROBIC DIGESTION OF SWINE WASTEWATER LIQUID FRACTION #60 Mesh Screen	81
19	ANAEROBIC DIGESTION OF BEEF CATTLE WASTEWATER LIQUID FRACTION #60 Mesh Screen	82
20	AEROBIC DIGESTION OF SWINE WASTEWATER LIQUID FRACTION	89
21	AEROBIC DIGESTION OF BEEF CATTLE WASTEWATER LIQUID FRACTION	91

SECTION I

CONCLUSIONS

The following conclusions have been derived from this study:

1. The removal of resistant solids from wastewater prior to stabilization substantially improves the performance of biological treatment systems by enhancing the controlling transport and kinetic mechanisms in such processes.

2. High efficiency removal of the resistant solids can be achieved on vibrating screen separators at costs which now make the solid separation step a feasible improvement on present designs of biological treatment systems for livestock wastewater.

3. The solids from the screen are odorless, stable and storable over extended periods without an odor-nuisance or pollutional problem.

4. The liquid fraction from the screen can be partially reclaimed by biological oxidation and recycled as transport water in confined livestock operation.

5. A rational procedure for performance evaluation and/or prediction of vibrating screen equipment for the separation of livestock wastewater solids has been developed. Since this appears to be the first reported case in which a systematic analysis of vibratory screen performance has been attempted, it is hoped that the general formalism developed would have a wide scope of application in aiding the design, specification and testing of this type of machinery in the future.

6. As a consequence of this study, a number of candidate livestock waste management designs integrating the salient features of the study have been proposed.

7. Sequential anaerobic/aerobic treatment of the liquid waste fraction shows promise. More complete treatment occurs in such a sequential process than can be expected in a strictly aerobic process of the same duration.

SECTION II

RECOMMENDATIONS

As a result of this study we are prepared to recommend:

1. Intensive future investigation concerning the value of the solid fraction of animal waste as a feed supplement for livestock. This type of study should include extensive feeding trials in which animal growth responses and health are closely observed as sole determinants of nutrient availability.

2. A recycle scheme is the most resourceful method of complying with extended winter storage regulations while minimizing odor nuisance, pollution potential and expense over the long haul.

3. In the hypothetical situation of a livestock producer operating a 1000-hog confinement unit with recycled flushing water and an aerated lagoon for treatment of same, an eighteen inch diameter vibrating screen separator operating thirteen hours per day will suffice.

4. Further intensive research of sand filters is needed before they can be considered a feasible means of animal waste solids-liquid separation. Hydraulic studies and management studies directed at plug-up problems should be given first priority in such studies.

5. In the hypothetical case mentioned above, a technically feasible system including an aerobic lagoon with diffused aeration, solid-liquid separator, pumping station and automatic flushing equipment could be constructed at an estimated 33,650 dollars (1970).

6. Floating aerators can be substituted into the above design to save approximately 5000 dollars (1970).

7. Since this study was strictly of a laboratory nature, there is a need to further prove aspects of these designs at the pilot scale before they can be considered fully operational. Such pilot studies should be directed toward defining the critical constraints on wastewater recycling, would provide large quantities of solids for feed trials and should provide more reliable information on the comparative costs and reliability of such systems.

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SECTION III

INTRODUCTION

General Remarks:

As we ponder the perplexing economic, social and political ramifications of agricultural operations structured within rapidly broadening boundaries of environmental responsibility, certain very recognizable patterns of the future begin to emerge. Among such traits can be seen quite distinctly some of the more obvious constraints within which future waste management systems in livestock operations must perform. Summarized into a broad statement of goals, it seems clear that the design of such systems must integrate:

(a) modern labor-saving methods of materials handling

(b) effective treatment techniques

(c) concepts in waste recycling into conservative closed or almost closed strategies limiting the total bulk of pollution and minimizing costs over the long haul.

One significant, relatively recent labor-saving development in animal waste management is the hydraulic handling and transport of animal manures in confined livestock operations. As a practice which lends itself readily to varying degrees of automation, it seems destined to continue to sustain high levels of acceptance in a circumstance in which present and projected shortages and high cost of labor have accentuated the need for even higher levels of automation on the farm.

Although the present use of hydraulic systems is almost exclusively restricted to confinement in-building operations, it could hold the key for dramatic improvements in the collection and handling of waste deposits in large open feed lots. Where such feed lots constitute air and water pollution hazards -- particularly close to large population centers -- it seems likely that these units may have to be paved so that hydraulic methods can be employed to achieve much higher levels of control of the waste management aspects.

As presently designed for hog and beef cattle production operations, hydraulic transport facilities range from modest water-filled pits and oxidation ditches under slotted floors to fairly sophisticated automated flushing devices of a variety of designs. Beside their labor-saving advantages, these systems make for an overall cleaner, safer, odor-free and more attractive environment for both the producer and the animals. However, irrespective of the particular design, large quantites of pollution-laden, odorous water emanate from these systems.

One popular method of managing this water at the present time is to provide temporary storage for it in in-building, outside, above-ground or

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underground storage tanks. If provided over the winter months when the ground is frozen and land application is inadvisable, such storage runs up a considerable expense. For Michigan and a substantial portion of the midwest region of the United States, a conservative estimate of minimum winter storage requirement is between 4 to 6 months. Costs of adequate facilities to provide such storage for a 1,000-hog farm has recently been estimated to be between $15,000-$25,000 in capital investment (1). When ultimately spread on the land following extended storage, untreated wet manure poses serious odor nuisance and water pollution problems which are responsible for an ever increasing number of legal suits. In the light of present and growing sensitivities at regional and national levels concerning environmental issues, a reasonable projection is that such litigations will occur with even greater frequency. It seems clear that livestock production must brace to make its operations compatible with maintaining the integrity of the environment.

An alternative to the store-and-spread practice considered above is the partial treatment of the pollution-laden wastewater by anaerobic, aerobic or combination biological processes intended to minimize the pollution potential of the wastewater and eliminate the odor nuisance problem prior to ultimate disposal on the soil. Abatement processes of this type are exemplified by the oxidation ditch, anaerobic and aerobic lagoons which are gaining considerable attention of late (2). In general the design of these treatment systems has been derived from sanitary engineering practice. It is recognized (2, 3), however, that animal waste slurries are much too loaded with high oxygen-demanding organic pollutants to permit the direct transfer of design information from the relatively dilute domestic or municipal wastewater with which sanitary engineering is normally concerned. The large number of treatment studies conducted over the past ten years show conclusively that certain design modifications are mandatory if biological processes are to meet with any degree of success in the treatment of highly polluted animal wastewaters.

As research continues to seek innovative modifications in conventional designs of biological processes that would make such processes more effective in the abatement of the unique odor and pollutional potential of animal wastewater, the essential reduction of the high solid matter in livestock wastewater prior to conventional biological treatment appears to be the one requisite task about which universal agreement currently exists among researchers. A sizable amount of these solids are non-biodegradable organics and salts whose presence in the treatment system effectively impedes transfer processes within the biological "reactor". In hog wastewater for example, such refractory or only slowly-biodegradable fraction amounts to about sixty to seventy percent of the total solids. The presence of these solids contributes significantly to the high viscous condition of the mixed liquor and thereby substantially increases the power demand of oxygenation and mixing equipment of mechanically aerated systems. It seems logical that the removal of these resistant solids would considerably improve treatment kinetics of aerobic and anaerobic biological processes. These improvements would in turn

enhance the potential to recycle the partially treated wastewater as wash and transport water for the hydraulic system. Considering the excessive concentration of oxygen-demanding pollutants in animal waste slurries, it is essential that treated wastewater rather than fresh water to recycled as a diluent to bring BOD and COD concentrations down to the recognized levels of high efficiency treatment.

The study reported here has evolved from the basic rationale that efficient solid-liquid separation of livestock wastewater is a necessary and integral part of any wastewater management scheme in which water is to be reclaimed and profitably recycled. The recycling of reclaimed wastewater offers the promise of minimizing capital investment costs on livestock wastewater management systems by substantially reducing the total bulk of water polluted and subsequently stored and/or processed.

Project Objectives:

The broad objective of this study is to develop the technical basis for a liquid manure processing system which (a) isolates the refractory component solids from livestock wastewater, and (b) subsequently handles the solid and liquid fractions in such a manner that they do not individually or collectively constitute an aesthetic or pollutional problem.

It is an implied prerequisite that the system remain within the recognized economic scale of the average livestock operator.

The specific tasks to which the study was directed are as follows:

1. To identify and carry out a comprehensive analysis of a technically and economically feasible solid-liquid separation system for livestock wastewater.

2. To characterize (physically, chemically and biologically) the solid and liquid component fractions.

3. To examine where necessary processes by which each component fraction can be reduced to a stable, storable or reusable end product with minimal odor nuisance or pollutional potential when ultimately disposed of on the soil.

4. To integrate the essential features of the above findings into least cost candidate designs at the pilot scale. It is hoped that one or more of these designs would constitute the basis for possible future large-scale demonstration studies.

Because of time constraints on the project, these objectives were carried out only for swine and beef cattle wastewaters.

Report Format:

In accordance with the outlined objectives, the report is presented in five major sections. The first part gives production and pollutional characterization data of beef cattle and hog manures determined in the preliminary stages of this study as compared to similar data presently available in the literature. The second part presents solid-liquid separation studies conducted on hog and beef cattle wastewater. Section three of the report deals with the characteristics of the component solid and liquid fractions. Section four presents data and conclusions on stabilization requirements of the solid and liquid fractions. Section five consists of a number of proposed pilot designs with cost projections which integrate aspects of the study.

SECTION IV

PRODUCTION RATES AND POLLUTIONAL CHARACTERIZATION OF HOG AND BEEF CATTLE MANURES

In summarizing his elaborate survey of existing data on the production and characteristics of animal manures, Loehr (2) concluded that published values vary due to differences in:

(i) housing and management practices

(ii) types of rations fed

(iii) analytical techniques employed

(iv) manure handling and collection techniques.

It therefore seems essential that investigators dealing with aspects of the animal waste problem should report the conditions under which the animals were fed and housed and the manner in which the waste samples were collected and analyzed so that a continuity can be maintained in correlating production and characterization data on these wastes. This part of the report is presented with this purpose in mind, and also as a data base for aspects of the study to be taken up in subsequent parts of the report.

Collection Facilities:

All the manure used in this study was collected from animals confined in individual metabolism cages. Figures 1 and 2 show the cages used for swine and beef cattle manure collection. The cage arrangement made it possible to collect the feces and urine separately. For the hogs, the feces were held up on the floor screens of the cage while the urine going through the screens was collected in narrow-neck plastic bottles. For the beef cattle, the animal was held in place (as shown in Figure 2) in such a way that the feces were discharged directly into a plastic bag and the urine was collected in funneled plastic bottles. One unique aspect of this arrangement is that evaporative losses were held down to a minimum in the urine.

Collection was done once a day at which time the urine and feces were weighed separately. In these categories, the manure was stored in its natural form without any added dilution water. Storage for short periods before use was done at 4°C. If preserved over extended periods, storage was done below freezing temperatures.

Feed Rations:

The animals used for collection purposes were in general experimental animals at the Michigan State University swine and beef cattle farms.

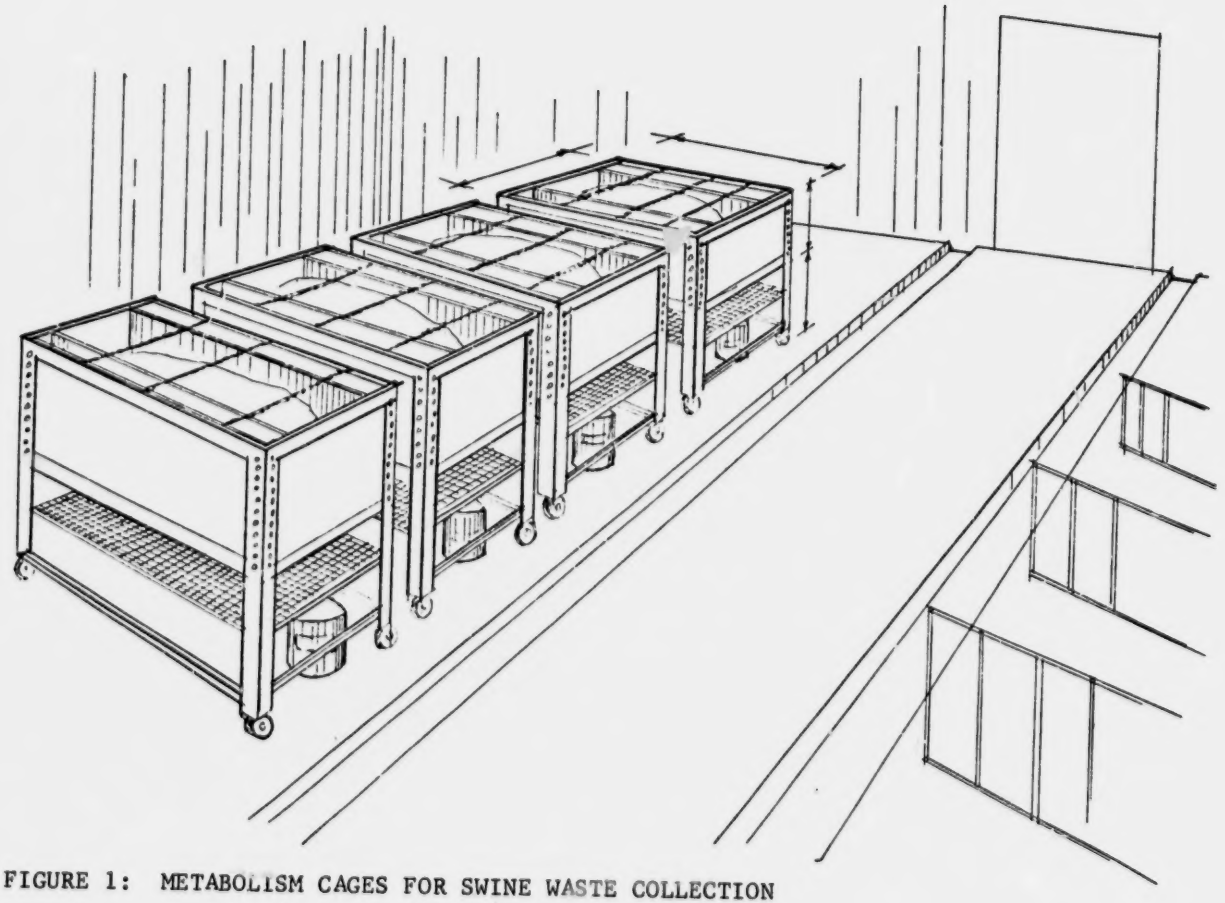

FIGURE 1: METABOLISM CAGES FOR SWINE WASTE COLLECTION

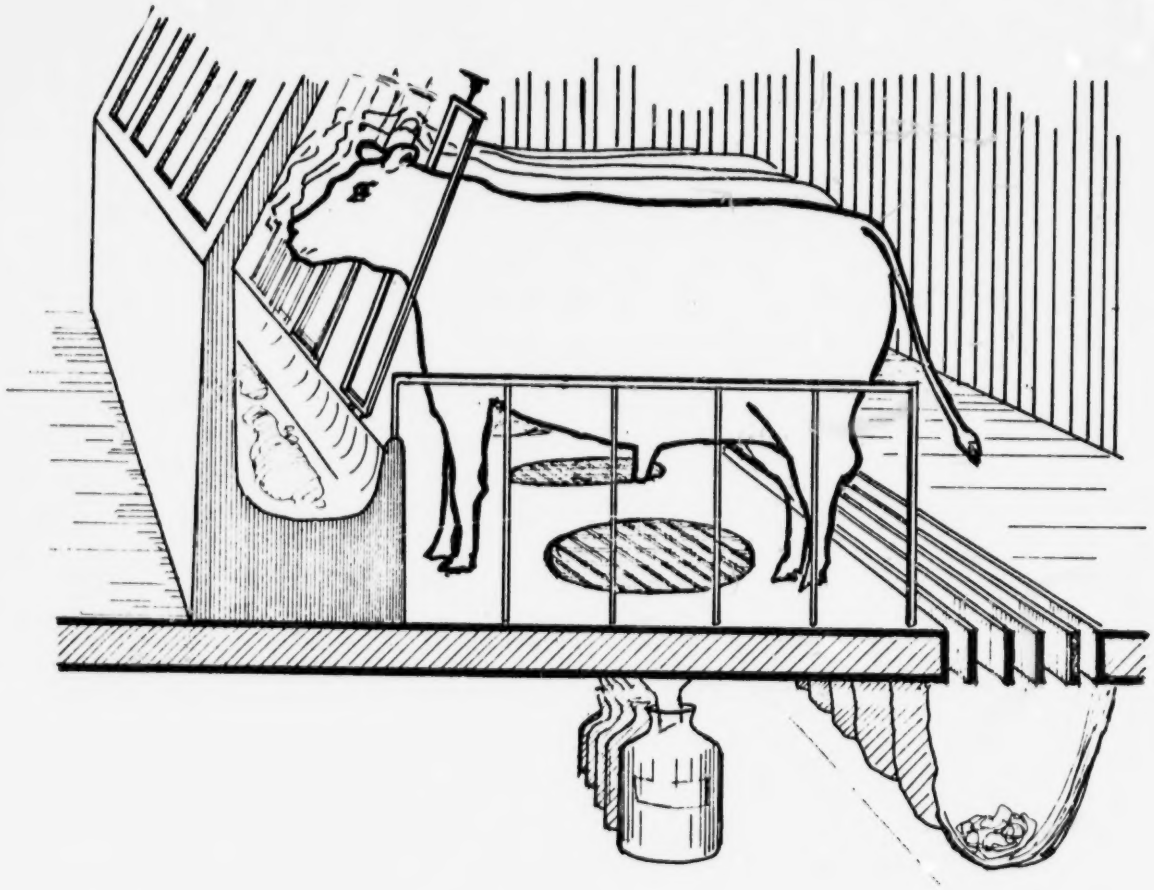

FIGURE 2: METABOLISM CAGES FOR BEEF CATTLE WASTE COLLECTION

For this reason the feeds given to these animals cannot be considered typical from a commercial standpoint.

The animals had access to as much water as they could possibly drink. They were fed once a day. A total of 5 hogs in different age groups were isolated in metabolism cages over periods varying from 3-10 week periods. The feed was primarily ground shelled corn (79%-86%) with 16%-13% protein supplement. In Table 3 a complete breakdown of the feed mix for the hogs is presented. Mineral analysis of the feed, feces and urine are tabulated in Table 5.

The primary feed for the beef cattle animals was corn silage of 35% dry matter. The feed is tabulated along with the defecation summary in Table 6. The animals had free access to water. The corn silage received some prestorage treatment which was part of an experiment being conducted by the Animal Husbandry Department.

Analytical Methods:

(i) Biological oxygen demand (BOD), chemical oxygen demand (COD), nitrogen, total solids (TS), and total volatile solids (TVS) were determined using procedures specified in Standard Methods for the Examination of Water and Wastewater (1965).

(ii) Phosphorus: was determined by first carrying out a perchloric acid digestion of the sample and then doing the final analysis on a photometric instrument. Reference: Methods of Soil Analysis, Vol. 9, Part 2 (13).

(iii) Nutrients and Minerals: (K, Ca, Mg, Zn, Cu, Fe, Mn, Na) were determined by first digesting the sample sequentially in nitric and perchloric acids and then doing the final analysis by flame photometry on an atomic absorption apparatus. Reference: Methods of Soil Analysis, Vol. 9, Part 2 (13).

(iv) Samples: In cases where composite samples were analyzed, the samples were composited as follows:

(a) hog wastes: 20% feces + 80% urine
(b) beef cattle wastes: 60% feces + 40% urine.

These percentage fractions were approximated from the collection data obtained in this study.

As a rule, nitrogen analysis was conducted as soon as possible following collection to minimize losses of the volatile forms which are known to occur.

Results and Discussion of Collection and Characterization Data:

The data obtained from this study on manure production rates and manure characteristics are presented in as complete a form as was considered necessary in Tables 2, 3, 4 and 5 for hogs and in Tables 6 and 7 for

TABLE 1: ANIMAL WASTE CHARACTERISTICS IN TERMS OF 1000 LB. LIVE WEIGHT

	Pork Pigs			Beef Cattle			Dairy Cattle	
	(a)*	(b)	(c)	(a)	(b)	(c)	(b)	(c)*
Raw Manure Production Rate (lbs/day)	50	50	28-95	35	--	63	88	38-74
Feces/total prod. (%)	25	50[d]	--	66	--	--	--	66
Total Solids (lbs/day)	5	7.2	8-16	4.9	--	9.5	9	9.5-11.4
Total Solids (% wb)	10	14.4	12-28	14	--	15	10	13-27
Volatile Solids (lbs/day)	4.1	5.9	3.5-8.0	3.8	--	3.17	7.2	5.7-8.3
Volatile Solids (% TS)	83	82	83-87	77	80	--	80	--
BOD_5 (lbs/day)	1.8	2.1	2.0-5.6	1.7	--	1.02	1.7	0.44-1.53
BOD_5 (lbs/lb of VS)	0.44	0.36	0.30-0.54	0.45	0.252	0.28-0.32	0.233	0.13-0.23
Reaction Rate Constant (log_{10})	0.8	--	--	0.14	--	--	--	--
BOD_5/COD (%)	44	33	19-45	38	--	31-40	16	8-23
Nitrogen (total Kjeldahl) (% TS)	7.0	5.6	3.3	6.2	9.8	3.1	4.0	3.5
(lbs/day)	.35	0.4	0.42-0.6	.30	--	--	0.36	0.35-0.44
P (% TS)	3.7	--	0.5-1.2	1.7	--	1.35	--	0.3-0.7
K (% TS)	3.49	1.4	1.3-3.2	2.27	--	3.0	1.7	1.8-3.8
Ca (% TS)	2.47	--	2.0-4.7	1.16	--	0.8	--	1.0-2.1
Mg (% TS)	1.20	--	0.3-0.65	0.47	--	0.65	--	0.4-0.8
Zn (% TS)	0.05	--	0.006	0.01	--	--	--	0.0015
Cu (% TS)	0.05	--	0.002	--	--	--	--	0.0005
Fe (% TS)	0.05	--	0.1-0.2	0.08	--	0.03	--	0.01-0.03
Mn (% TS)	0.02	--	--	0.01	--	--	--	--
Na (% TS)	0.63	--	--	0.09	--	--	--	--

*Column (a) values obtained by authors of this report (1971)

Column (b) average suggested values by Taiganides (1971)

Column (c) range of tabulated values by Loehr (1968)

Column (d) Taiganides (1962) Ph.D. Thesis

Column (c)* calculations based on tabulated values by Loehr (1968)

TABLE 2: SWINE INPUT-OUTPUT SUMMARY

Trial Number	Period (Week)	Average weight (lbs)	Rate of gain (lbs/day)	Feed Rate (lbs/day)	Feed: Water Ratio	Feed Ration (% Protein)	Efficiency (lb feed/ lb gain	Elimination Rate (lbs/day) (Feces + Urine)	Elimination Rate lbs/day / 1000 lbs live weight	Parts urine to one part feces	Elimination Rate as Percent of Feed-Water Intake.
(1)	1	55		2.2				2.65	48	2.5	
initial wt	2	60		2.2				2.5	42	3.0	
52 lbs	3	67		3.3				3.0	45	2.3	
final wt	4	76		3.3				5.3	69	3.0	
110 lbs	5	87		4.4				5.6	64	3.0	
	6	100						4.2	44	2.1	
AVERAGE			1.3		1:2	16	2.6		52	2.6	45
(2)	1	102		3.3				4.3	42	2.5	
initial wt	2	110		3.3				5.7	51.5	3.9	
97 lbs	3	118		3.3				4.5	38	3.65	
final wt	4	124		4.4				5.4	43	3.7	
168 lbs	5	136		4.4				6.0	44	3.55	
	6	156		5.3				6.5	41.5	3.7	
AVERAGE			1.6		1:2	16	3.9		43	3.4	48
(3)	1	142						5.6	39.5	2.9	
initial wt.	2	150						6.3	41	2.4	
138 lbs	3	158						4.8	30.5	1.8	
final wt	4	164						6.0	36	2.6	
179 lbs	5	173						6.3	36.5	3.0	
	6	178						6.1	34	2.6	
AVERAGE			1.05	4.4	1:2	13	4.3		36	2.5	46
(4)											
initial wt	1	168						6.0	36	3.5	
164 lbs	2	175						5.9	33	4.5	
final wt	3	178						5.9	33	4.0	
180 lbs											
AVERAGE			0.9	4.4	1:2	13	5.5		34	4.0	45
(5)											
initial wt	1	57		2.5				4.6	80	5.0	
53 lbs	2	64		2.5				4.6	71	4.75	
final wt	3	73		2.5				5.3	69	5.25	
90 lbs	4	81		5.2				5.8	72	4.9	
AVERAGE			1.1		1:3	16	2.7		73	4.7	44
AVERAGE OF ALL TRIALS									50	3.4	45
Average values by weight range		40-80							70		
		80-120							50		
		120-160							42		
		160-200							34		

beef cattle wastewater. Along with the production and characterization information are presented complementary data about feed rations, animal sizes and rate of weight gain which are considered relevant.

In Table 1, a summary of all this data is developed and presented in comparison with the most widely accepted values in the current literature.

Overall, there are no differences which cannot be explained on the basis of differences either in collection practices or in feed rations. In this connection, it is essential to note that animals confined in cages such as used in this study do not exercise enough and therefore may eat and defecate in rather unusual patterns. The methods of analysis for nutrients and minerals used in this study are believed to be better than most used previously in animal waste studies. Differences in analytical techniques may account for some of the differences observed in nutrient and mineral values.

TABLE 3: SWINE FEED MIX

	16% Protein	13% Protein
Ground Shelled Corn	79%	85.5%
Soybean Meal	18	11.5
Dicalcium Phosphate	1.0	1.0
Ground Limestone	1.0	1.0
Trace Mineral Salt	0.5	0.5
MSU Vitamin-Trace Min Mix	0.5	0.5
	100.00%	100.00%

TABLE 4: POLLUTIONAL CHARACTERISTICS OF SWINE WASTE

Weekly Composites	COD (mg/l)	BOD_5 (mg/l)	TOTAL N (mg/l)	NH_3 - N (mg/l)	% NH_3 - N OF TOTAL N	% TS*	% VS
1	86,000	32,000	8540	4611	54	8.7	80
2	76,000	30,000	7000	3780	54	8.0	84
3	61,000	27,000	5600	2856	51	6.3	82
4	68,000	29,000	5950	2915	49	5.6	83
5	90,000	47,000	9170	3668	40	9.56	83.3
6	80,000	43,000	6160	3449	56	8.00	83
7	74,000	41,000	6500	1950	30	8.3	82
8	69,000	29,000	6000	3240	54	8.5	83
9	81,000	44,000	8000	4240	53	10.5	84
10	70,000	30,000	5900	3186	54	8.2	81
Average	80,000	35,000	6880	3390	49	8.16	83

* Average less than normal because of greater than normal water intake.

TABLE 5: MINERAL ANALYSIS -- (FEED, FECES, URINE) SWINE

	Feed 13% Moisture	Feces 65% Moisture (Trial 1)	Feces 65% Moisture (Trial 2)	Urine 96% Moisture (Trial 1)	Urine 96% Moisture (Trial 2)
Ca (ppm)	7,980	27,780	22,520	168	511
Mg (ppm)	1,690	9,300	6,740	68	109
Zn (ppm)	106	432	585	3.1	1.5
Cu (ppm)	19	117	98	.16	.17
Fe (ppm)	140	513	398	1.1	1.2
Mn (ppm)	34.7	213	140	.32	.31
Na (ppm)	2,170	3,060	2,210	1,510	1,090
K (ppm)	5,930	11,730	8,770	2,300	2,330
P (ppm)	6.450	18,110	15,360	224	133
S (ppm)	3,960	1,010	1,070	980	1,230
N (ppm)	24,700	34,800	34,400	5,190	4,770
Expressed as Grams/Gram Solids					
Ca	.009172	.078474	.063615	.0041379	.01258
Mg	.0019425	.026271	.019039	.001674	.002684
Zn	.001218	.001220	.0016525	.0000763	.0000369
Cu	.00002183	.0003305	.000276	.0000039	.0000041
Fe	.0001609	.001449	.001124	.000027	.0000295
Mn	.0000398	.0006016	.000395	.000008	.0000076
Na	.0031149	.008644	.0062429	.037192	.026847
K	.006816	.033135	.024774	.056650	.057389
P	.0074137	.0511582	.043389	.005517	.003275
S	.0045517	.002853	.0030225	.024137	.03029
N	.0283908	.098305	.097175	.12783	.11748

TABLE 6: FEEDER CATTLE INPUT-OUTPUT SUMMARY

(one week trials, 3 animals in each weight division)

	Feed**			Waste	
Live Weight (lbs)	Rate (lbs/day)	% Shelled Corn	% Mineral Supplement	Elimination Rate (Feces+Urine) (lbs/day)	Fecal Material (as collected) (lbs/day)
750	38	--	5	22	12
750	38	21	5	28	17
750	33	25	*	28	19
750	37	3	-	51	30
1100	39	55	4	37	19
1100	40	52	9	38	17.5
1100	40	55	4	36	23
1100	40	52	9	38	17.5
750	35	--	*	17	13
750	35	--	*	27	20
750	37	--	2	30	25
750	34	--	-	28	19

**Primary feed was corn silage 35% dry matter in all cases

Free access to water

*Pre-storage treated corn silage

TABLE 7: MINERAL ANALYSIS -- BEEF CATTLE WASTE

Composite: 60% feces + 40% urine

	Expressed as PPM	Expressed as % TS
Ca	1,700	1.16
Mg	690	0.47
Zn	18	0.012
Cu	27	0.035
Fe	122	0.083
Mn	16	0.011
Na	130	0.088
K	3,350	2.28
PO_4	7,750	5.27

SECTION V

SOLID-LIQUID SEPARATION STUDIES

Preliminary Considerations:

Recent studies (4, 5) on solid-liquid separation of livestock wastewater appear to have established that solid removal efficiencies in excess of 90% can be readily achieved in standard sludge handling equipment such as centrifuges and vacuum filters. However, a cost survey undertaken at the preliminary stages of this study showed conclusively that capital investment costs on centrifuges, presses and vacuum filters far exceed what can be considered feasible for the average operator.

It was decided early in the project to exert the major research effort on more realistic solid separation processes. Several chemical flocculants were first examined. These included ferric chloride solutions and and a whole series of anionic, cationic and nonionic polyelectrolytes with -- and without -- pH adjustment. Although a number of these flocculants were effective in concentrating the solids, they invariably produced an odoriferous sludge which had further to be processed or else would constitute a major odor nuisance problem when ultimately spread. It was felt in addition that the close supervision necessary to operate a chemical process of this nature would be beyond what one can realistically expect at the level of the individual operator. Besides, the cost of chemicals would be a continuing expense which can become quite tangible over time. For these reasons, it was decided that chemical flocculation per se was both insufficient and operationally unfeasible.

Attention was subsequently turned to mechanical gravity-dewatering devices. Of the two recognized gravity units known to be used for sludge dewatering, the mechanical vibrating screen separator is more easily accessible, more versatile and less expensive than the centrifuge (6). In solid liquid separation operations, this type of screen provides superior quality separated solids since the vibrating action simultaneously washes and squeezes the solids to a cleaner and drier end product. In 1968, a University of California Agricultural Extension Bulletin authored by Fairbank and Bramhall (7) reported the first documented case in which a vibrating screen separator was used for the fractionation of livestock wastewater. In their experience with dairy wastes in California, Fairbank and Bramhall emphasized the solid washing characteristics, mechanized or semi-automated operation and superior capacity to handle large volumes of flow as the primary advantages of rotating or vibro-energy separators. They observed in particular, that the separated solid fraction exhibited a high degree of apparent stability, was fibrous, relatively odor-free, non-fly attracting and can be stored for extended periods. These observations, though qualitative in nature and scientifically inconclusive, showed a very high degree of correspondence with the solid quality criteria considered desirable. A cost survey was conducted which showed that capital outlay on this type of equipment lies well

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within the $1,000-$5,000 margin which we considered comfortable. The machine is mechanically simple, easy to operate and requires very minimal maintenance. These attributes were considered very desirable features.

Preliminary tests with laboratory ro-tap reciprocating sieves indicated that solid removal efficiencies between 50%-70% are well within reach for swine and beef cattle wastewater on screens ranging in mesh size from 60 to 120. The resulting solid residue had moisture content between 70 and 80 percent (wet basis), had a friable non-clumping structure, was odor-free, and when left exposed over extended periods attracted no flies. The effluent liquid from the screen contained small particulates which settled slowly and had a high percentage of matter in the colloidal range. Small scale digestion tests in anaerobic digesters indicated that at dilutions of 1:5 and 1:10, over 90% of the volatile suspended solids were dissipated in 5 to 10 days at 95°F. It was inferred from these observations that biological processes preceded by solid separation in a vibrating sieve could hold interesting prospects.

Engineering Analysis of the Vibrating Sieve Separator

In spite of the fact that vibrating screens were used in Germany as far back as 1954 (8) for sludge dewatering and have been in extensive use as a multi-purpose separator in a wide variety of industries since then, there does not exist today any satisfactory method by which this equipment can be selected to do a particular job. The usual method of selection is on the basis of tests with smaller geometrically similar machines. However, the installation of such machines for testing purposes is sometimes not possible, or the supply of sample wastewater may be limited (as for example from a small pilot plant). Under these circumstances it is not possible to predict the performance of large scale vibratory separators.

The purpose of this section of the study is to attempt to provide a rational basis for quantitative performance evaluation of vibrating sieve separators when used for solid separation of livestock wastewater. The study carried out so far is limited to:

(i) beef cattle and swine wastewaters and

(ii) only one type of vibrating sieve machine -- namely that which derives its basic vibrational action from the interaction of suspension drive springs and rotating weights subjected to known angular acceleration.

It is hoped that the general method of attack will have a much wider scope of application. However, as a note of caution, it is essential to state at this stage that there can be no real substitute for performance ratings based on actual tests on geometrically and functionally similar machines. The effectiveness of such tests, the broad interpretation of their results and the logical scale-up of such results can be considerably improved by generalized methods of analysis such as will be presented.

Basic Operating Principles:

The machine used in this study is the Sweco Vibrating Screen Separator manufactured by the Southwestern Engineering Company of Los Angeles. Although the selection of this particular machine was strictly a matter of convenience, it is very typical of vibrating screen separators which derive their excitation from rotating weights. It is also one of the two leading brands in industrial use. The 18-inch diameter model of this machine was borrowed from a local distributor for the purpose of this study.

The essential component parts of the machine are shown diagramatically in Figure 3. Successful solids separation with the machine depends on the accomplishment of a number of distinct processes. The first step is to achieve a pattern of travel over the screen cloth that will give the efficiency and final product desired. This pattern varies with the characteristics of the material, rotational speed of the drive motor, the magnitude and setting of the bottom and top weight assemblies. The gross vibrational force can be attributed to a complex, multi-dimensional general acceleration function of sinusoidal origin whose precise representation is not possible. However, a useful simplification is to consider the effective components of the vibrational force in the vertical and horizontal directions. The vertical component force is responsible for vertical motion of particles on the screen and imparts a compressive action on the solids tending to squeeze out the liquids. The horizontal component force is responsible for the horizontal material flow pattern which moves the dewatered solids out. The pattern of travel on the screen is regulated by the degree of lead (lead angle) of the adjustable "bottom motor weight" with respect to the "top motor weight". The relative size of the weights, and the phase differential in their angular rotation affect the vibrational force distribution in the vertical and horizontal planes. These parameters must therefore be expected to vary with wet and dry materials, particle size, moisture content, percentage solids, density, opening size of screen cloth, screen analysis of feed, feed rate and the desired capacity and efficiency.

A distinct step which deserves a special mention is the "roping" or "balling" phenomenon which plays a very important role in determining materials travel patterns on the screen. These balls form either as individual agglomeration of particles or as connected balls. Balling appears to be very closely related to moisture content and consistency of the separated solids. Under steady state conditions on the screen, balls form readily when the material consistency is such that rolling friction on the screen is just overcome by the resultant of the vertical and horizontal component forces. The ball sizes result from the interaction between vibrational and sliding frictional forces on the screen surface. In Figure 4 an illustration of the average material travel patterns on the screen is presented.

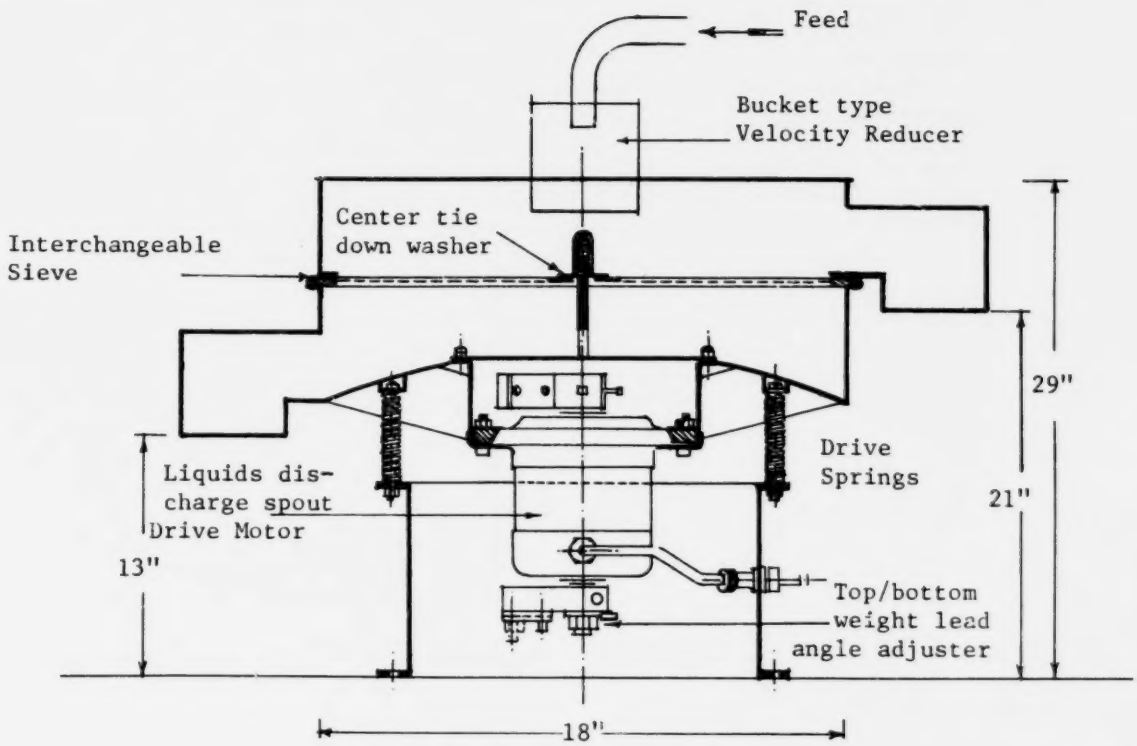
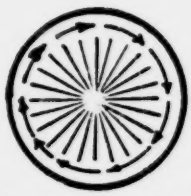


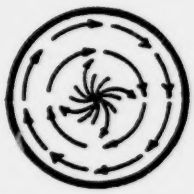
FIGURE 3: VERTICAL SECTION THROUGH A BASIC SINGLE DECK, 18" SWECO VIBRATING SCREEN SEPARATOR



0° Lead - Average material may be thrown straight and may give insufficient separation.

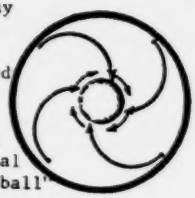
15° Lead - Average material may begin to spiral.

40° Lead - May give average dry material maximum efficient screening pattern.



60° Lead - May give average wet material maximum efficient screening pattern.

Maximum Lead may keep oversize material from being discharged and assist in receiving maximum thruput of minus material which tend to "ball"



Roping Pattern on the screen

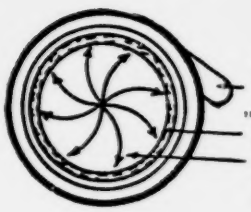


FIGURE 4: ILLUSTRATION OF AVERAGE MATERIAL TRAVEL ON SCREEN

Analysis of Vibratory Screen Performance:

As a solid-liquid separator, the vibrating screen should perform two functions:

(i) produce a clean centrate, and

(ii) produce a clean low-moisture cake.

The two obvious measures of performance would therefore be (a) centrate suspended solids concentration and (b) cake solid concentration or moisture content.

It is customary in the estimation of centrifuge and vacuum filter sludge dewatering performance to define performance in terms of percentage solids removed. It is convenient to adopt this practice here. We therefore define performance designated by a symbol R, where:

$$R = \frac{\text{wt. of solids in sludge cake}}{\text{wt. of solids in the feed}} \times 100 \qquad (1)$$

It is convenient to use a form of equation (1) in which only concentration terms are employed, so that

$$R = \frac{C_k\ (C_f - C_c)}{C_f\ (C_k - C_c)} \times 100 \qquad (2)$$

where C_f = feed solids concentration

C_k = cake solids concentration

C_c = centrate solids concentration

Equation (2) is approximated by a simpler more convenient form:

$$R = \frac{C_f - C_c}{C_f} \times 100 \qquad (3)$$

Variables Affecting Vibrating Screen Performance:

The paramount variable affecting vibrating screen performance is obviously the design. Even though each design would have certain peculiarities, there are a number of variables which can be generalized for all machines which work on the same basic vibrational principle. These can be delineated into two broad categories of parameters -- namely process and machine variables. From the previous discussion on the operating principles of this type of machinery a summary table of these variables has been prepared (Table 8).

Obviously this list is formidable. It does not seem likely that with so many variables we can intelligently and coherently discuss vibratory sieve performance. It is therefore necessary to abridge this list to

manageable proportions. We need to first assume that we are dealing with a particular machine separating a particular wastewater. The pertinent machine variables now become:

(i) Magnitude of top and bottom weights, (W_t and W_b respectively; lb_f)

(ii) Lead angle between top and botton weights (ϕ; dimensionless)

(iii) Percentage opening of screen (ξ; dimensionless)

(iv) Screen mesh size (D_s; ft)

(v) Effective surface area of screen (A; ft^2)

The pertinent process variables are:

(i) Average particle size (D_p; ft)

(ii) Flow rate of feed (Q; ft^3/sec)

(iii) Residence time (τ; seconds)

(iv) Centrate density (ρ_c; $\frac{lb_m}{ft^3}$)

(v) Centrate viscosity (μ_c; $\frac{lb_m}{ft\text{-}sec}$)

The third process variable, τ, is considered to be very important since it lumps together into one variable all material characteristics and those machine-material interactions which we cannot easily characterize individually. One obvious example of this is the material properties

TABLE 8: VARIABLES AFFECTING THE PERFORMANCE OF VIBRATING SCREEN SEPARATOR

Machine Variables	Process Variables
Screen diameter	Residence time on screen
Screen mesh size	Material characteristics
Screen percentage opening	Particle size of particles
Rotational speed of motor	Particle shape
Top and bottom weights	Particle density
Lead angle between top and bottom weights	Rheology
Number of springs	Solids concentration
Spring constants	Chemical additives and quantities
Feed point	Liquid viscosity
Degree of artificial feed -- velocity dissipation at feed point	Liquid density
	Feed rate of liquid

and their interaction with screen surface frictional forces, and with vibrational force distributions to bring about balling. It seems quite clear that any attempt to gain exclusive insight into this complex phenomenon would be futile. However, all these forces and a lot more play an important part in determining the average length of time the individual particle stays on the screen before it is discharged under steady state conditions. This quantity τ also provides us with a concrete way of selecting optimum performance conditions on the screen. Any combination of machine variables and process variables which gives the smallest τ value for the same cake moisture content and centrate suspended solids concentration can be considered optimal.

Development of Model:

If a model is to represent vibrating screen performance accurately, it must include the essential variables necessary for screen performance. From the preceding discussions, the general form of any such model can be represented using methods of dimensional analysis such that:

$$\text{Recovery} = f\ [(\text{machine variables}), (\text{process variables})]$$

Using equation (3) and the abridged list of pertinent variables, we can represent the above relation in the following form:

$$R = \frac{C_f - C_c}{C_f} \times 100 = f(W_t, W_b, \phi, \xi, D_s, A, D_p, Q, \tau, \rho_c, \mu_c) \quad (4)$$

We can reduce the number of variables in equation (4) considerably by defining a modified rate of flow (q) such that

$$q = \frac{Q}{A\xi}\ , \ \left(\frac{ft}{sec}\right) \quad (5)$$

Equation (4) now becomes:

$$\frac{C_f - C_c}{C_f} \times 100 = f\ (W_t, W_b, \phi, D_s, D_p, q, \tau, \rho_c, \mu_c) \quad (6)$$

The quantity q has the units of velocity and represents the flow rate per unit surface area of the screen going through the screen openings.

Employing the Buckingham Π theorem, we can form the following dimensionless groups:

$$\Pi_1 = R = \frac{C_f - C_c}{C_f} \times 100, \text{ (percentage removal)}$$

$$\Pi_2 = \frac{D_s}{D_p}\ , \text{ (ratio of effective particle size and screen size)}$$

$$\Pi_3 = \frac{q\tau}{D_s} \text{ , (dimensionless residence time)}$$

$$\Pi_4 = \frac{q\ \rho_c\ D_s}{\mu_c} \text{ , (dimensionless rate of throughput)}$$

Note that Π_4 is a form of modified Reynolds number derived for the centrate and using screen mesh size as the characteristic dimension. Under steady state conditions, for feed solids concentration below 5%, the centrate rate of flow measured volumetrically approximates the feed rate of flow. The choice of centrate properties in defining Π_4 is therefore a matter of convenience since a term like viscosity is easier to measure for suspensions in which the rate of settling of solids is slow enough so that medium characteristics during measurement remain reasonably unchanged. Also the density of the centrate closely approximates that of water at the same temperature.

$$\Pi_5 = \frac{W_b}{W_t} \text{ (dimensionless weight ratio)}$$

Since the magnitude of the bottom weight assembly as compared to the top weight assembly affects the force distribution in the horizontal and vertical planes, the ratio Π_5 is a simple measure of the relative effect of these component vibrational forces in two planes.

$$\Pi_6 = \phi \text{ (lead angle)}$$

It was previously stated that the lead angle regulates travel patterns on the screen. This parameter must therefore have a strong effect on residence time.

There is at least one more dimensionless quantity which can be defined involving the resultant vibrational force, F. This quantity would take into account the angular acceleration responsible for the vibrational force and can take the form of a modified Euler Number, $F/q^2D^2\rho^2$. However, since the angular velocity is usually fixed for a given machine, this quantity may be quite superfluous. It is particularly undesirable since F is practically impossible to determine explicitly in a real machine. Since we have already attained a sufficient representation of the pertinent parameters in the first six dimensionless groups, we can meaningfully characterize the system without a 7th group.

Equation (6) can now be written as

$$\Pi_1 = \lambda\ (\Pi_2,\ \Pi_3,\ \Pi_4,\ \Pi_5,\ \Pi_6)$$

or

$$\frac{C_f - C_c}{C_f} \times 100 = \left(\frac{D_s}{D_p}\ ,\ \frac{q\tau}{D_s}\ ,\ \frac{q\rho_c D_s}{\mu_c}\ ,\ \frac{W_b}{W_t}\ ,\ \phi\right) \qquad (7)$$

since the percentage removal is directly related to both effective particle size and screen mesh size we can extract Π_2 from the parenthesis to

obtain:

$$\frac{D_p}{D_s}\ \frac{C_f - C_c}{C_f} \times 100 = \lambda \left(\frac{q\tau}{D_s}, \frac{q\rho_c D_s}{\mu_c}, \frac{W_b}{W_t}, \phi\right) \qquad (8)$$

The left hand side of equation (8) being the product of two dimensionless groups remains dimensionless. Note, however, that for the same screen size and the same material, the dimensionless quantity on the left hand side will remain effectively constant irrespective of the other variables.

With the number of dimensionless variables specified in equation (8), it is not possible to proceed directly to set up an explicit functional predictive relationship between the variables. One simplification which can make this task less burdensome is to specify a steady state constraint on the performance variables. As a continuous flow machine, the vibrating screen separator relies very much on steady state conditions for good performance. The pertinent process variables must be adjusted to achieve a state of equilibrium on the machine. For a given set of machine variables represented typically by $(\phi, \frac{W_b}{W_t})$, the rate of feed must be adjusted until a condition approximating steady state performance is observed on the screen. Under this condition, a characteristic flow pattern maintains a steady stream of cake coming out of the screen. Our study so far indicates that as long as measurements are taken under a state of equilibrium, the cake maintains a uniform moisture content for the same feed material irrespective of the combination of machine and process variables necessary to generate equilibrium.

With the steady state constraint on the model, there are a number of alternative paths along which we can proceed. One one considered most expedient is to approach the problem in two basic steps:

1. The Optimization Step: in which we extract from equation (8) a general residence time function in the form:

$$\frac{q\tau}{D_s} = \lambda_1 \left(\frac{W_b}{W_t}, \phi\right) \qquad (9)$$

It is now possible to define an optimum residence time within carefully specified limits by seeking a minimum for equation (9). The experimental data obtained from vibrating screen performance tests on swine wastewater have been used to graphically represent the nature of equation (9) in Figure 5.

This plot shows clearly that the equilibrium values of dimensionless residence time when plotted as a function of lead angle with the bottom-top weight ratio as a parameter, has well defined minima. Each minimum point in Figure 5 represents an optimum residence time obtainable from the combination of machine and process variables (D_s, W_b/ W_t, ϕ, q) making up the plot. For a given screen, the curve giving the smallest optimal dimensionless residence time as well as an optimal top-bottom

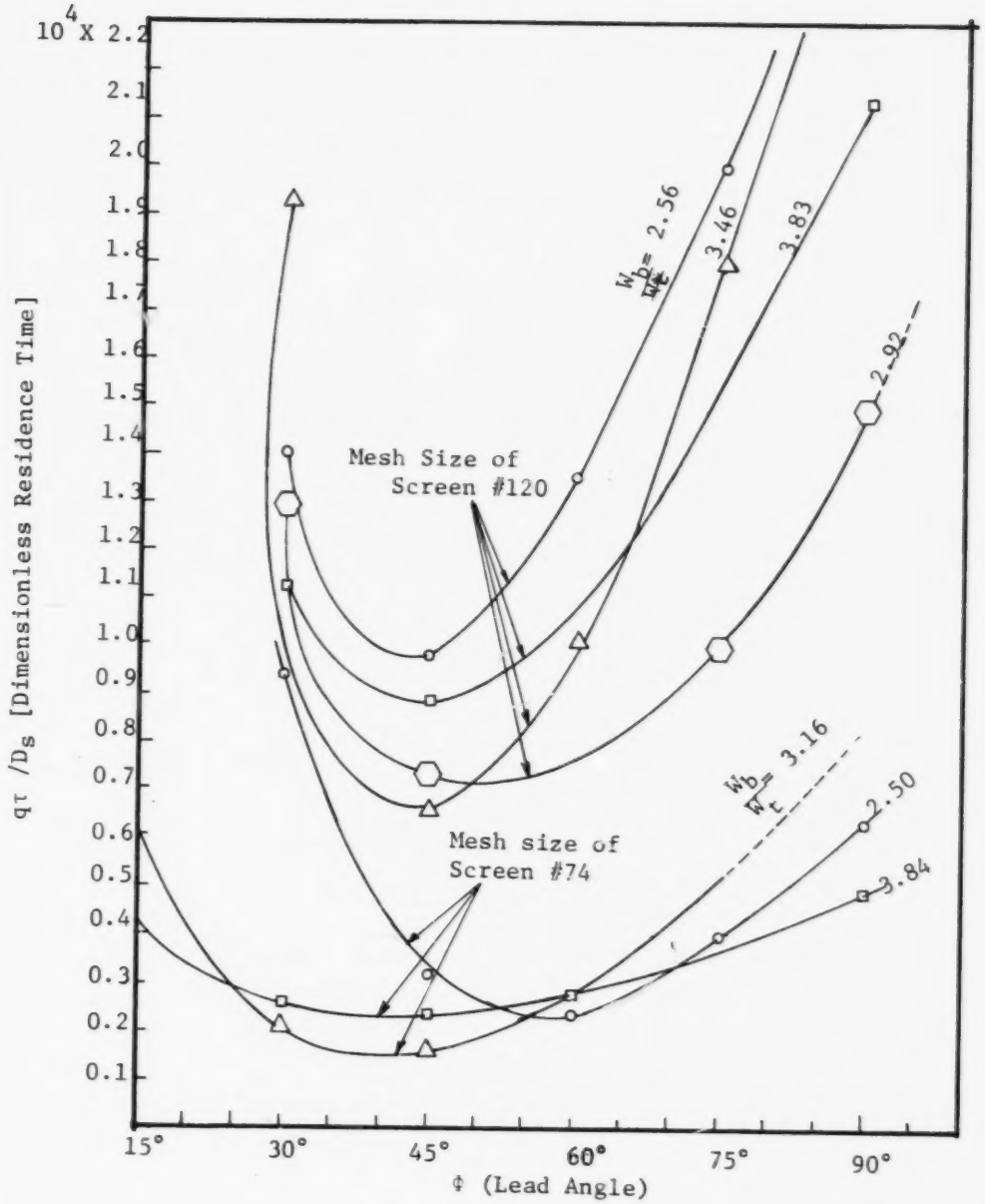


FIGURE 5: OPTIMIZATION PLOT FOR SWINE WASTEWATER

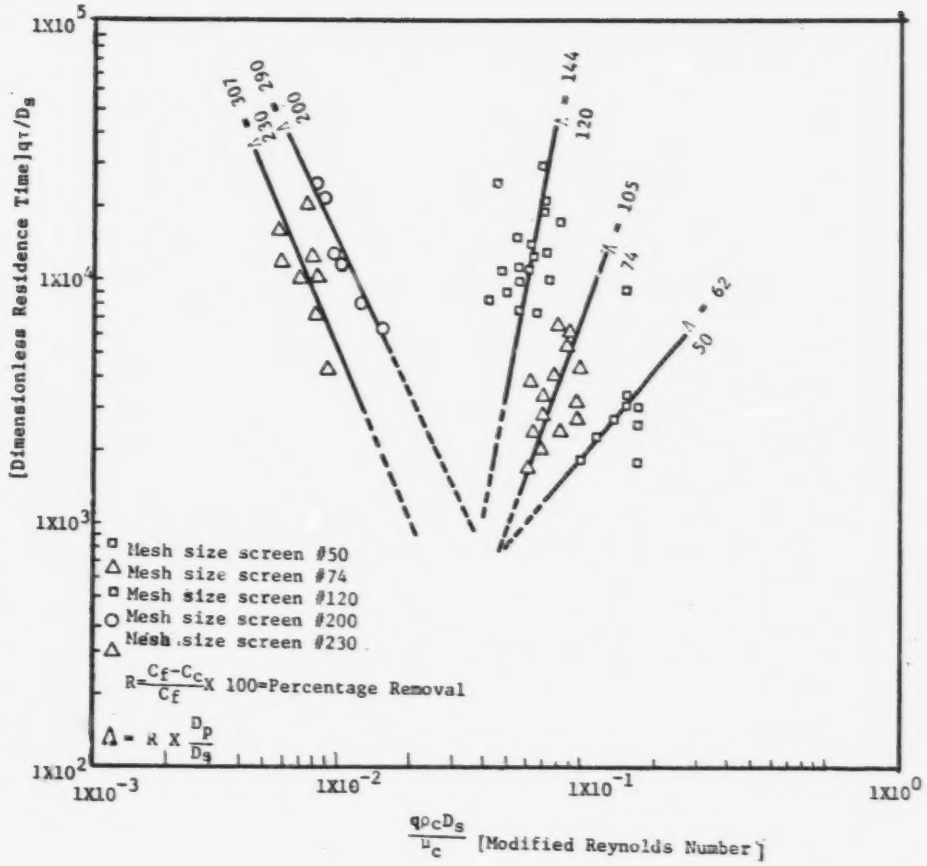


FIGURE 6: PERFORMANCE CURVES FOR SWINE WASTEWATER

weight arrangement using this general procedure.

For swine wastewater, Figure 5 shows that the best residence times for screen mesh sizes #74 and #120 occur when the top-bottom weight ratios are respectively 3.16 and 3.46. The experiments on which the plots are based will be described in detail in a subsequent section. It is appropriate to mention here, however, that these experiments were sufficiently exhaustive to permit some generalization of their results.

2. Design Step: with optimal constraints already specified for ϕ and W_b/W_t in step 1, it is now possible to simplify equation (8) to the form:

$$\left(\frac{C_f - C_c}{C_f} \times 100\right) \frac{D_p}{D_s} = \lambda_2 \left(\frac{q\tau}{D_s}, \frac{q\rho_c D_s}{\mu_c}\right) \qquad (10)$$

Equation (10) is rearranged to the form

$$\frac{q\tau}{D_s} = \lambda_3 \left(\frac{q\rho_c D_s}{\mu_c}, \Lambda\right) \qquad (11)$$

where $\Lambda = \left(\frac{C_f - C_c}{C_f} \times 100\right) \frac{D_p}{D_s}$

Experimental data obtained from vibrating screen tests on swine wastewater are plotted in Figure 6 in accordance with equation (11). The raw data from which this plot is developed will be discussed in great detail subsequently. Figure 6 expresses the dimensionless residence time ($q\tau/D_s$) as a function of the modified Reynolds number ($q\rho_c D_s/\mu_c$) with the dimensionless quantity, Λ, as a parameter. It is apparent that very distinctive patterns of behavior can be discerned from the plot. In terms of the dimensionless parameters of the plot, the screens appear to have well defined exponential performance characteristics. Each screen has a range of Reynolds number in which its performance, defined in terms of percentage solids removed and throughput capacity, is optimal. The residence time of the solids on the screen which matches this optimal performance level must be selected from the preceding step in which the residence time was optimized in terms of machine variables.

While basically incomplete, the system of curves in Figure 6 is believed to provide a sufficient coverage of the region of practical interest. Experience with solid separation of both swine and beef cattle wastewater indicates that mesh screen sizes between #50 and #120 are most practical. Screen sizes below this range would permit greater capacity throughput at the expense of solids removal efficiency. On the other hand, above the range, throughput capacity is drastically reduced without significant improvements in solids removal. Within the recommended range, we feel that interpolation or extrapolation of the system of curves in Figure 6 can be carried out with reasonable validity.

For each specified wastewater, it will be necessary to develop a chart similar to that of Figure 6 as a design aid in equipment selection and ultimately as an operational guide for the estimation of performance rating of machines. For purposes of design, if a small model of the machine can be obtained, the procedure presented provides a comprehensive framework within which a test can be most effectively conducted and the data so obtained can be put to the best use. Where it is not possible to obtain a small test machine, a first estimate of machine size necessary to accomplish carefully defined objectives can be made with the aid of the curves and with the general procedure presented.

The Effect of Sludge Conditioning on Performance Rating:

It is customary in performance evaluation of dewatering centrifuges, presses and vacuum filters to consider the effect of sludge conditioning on performance rating. Sludge conditioning refers to the pretreatment of the sludge by the addition of chemicals such as coagulants, flocculants, pH control, or predigestion under anaerobic conditions. Limited tests in this study indicated that chemical conditioners had little or no effect on the performance of vibrating screen separators. This observation is not surprising since vibrating screens do not depend on settling characteristics of the solids for their performance. The bridging forces which encourage the agglomeration of particles when chemical conditioners are added to sludge appear to be destroyed by vibrational forces on the screen. Consequently their effect, if there is one, is negligible.

Sludge age and sludge digestion under anaerobic conditions were found to change the flow properties of the solids on the screen. In general, the solids appear to be experiencing greater difficulties in forming balls. The optimum moisture content appears to change to a value slightly lower than the corresponding balling moisture content of fresh solids. The throughput capacity under these conditions appears to be measurably reduced. These observations, though vague, are intended to stimulate interest in further exploration of this particular feature. Within the broader context of our overall study, it was not considered advantageous to predigest the solids prior to separation since this would add an additional step and cost to the process. With this basic disposition, no real concerted effort was made to quantify the effect of pre-digestion on screen performance. It is recognized, however, that there may be circumstances under which sludge conditioning by anaerobic digestion would be desirable.

Experimental Procedures and Results:

1. Methods of Sieve Analysis: The wet method of sieve analysis adopted from the 1970 edition of Tyler Handbook #53 was used to estimate the solids removal potential of vibrating screen separators. The complete set of results obtained from sieve analysis of swine wastewater is presented in Table 9. A somewhat less extensive analysis of beef cattle wastewater is given in Table 10.

TABLE 9: SIEVE ANALYSIS AND THE REMOVAL PERCENTAGE ESTIMATES OF SWINE WASTEWATER SOLIDS

Soaking Time	Mesh Size of Screen	Percentage Removal (%)		
		1.2% TS	2.72% TS	5.44% TS
1 Hour	20	44.2(%)	55.6(%)	51.2(%)
	48	51.6	60.7	55.6
	60	54.9	61.4	57.6
	100	56.3	63.5	58.9
	200	----	63.9	60.9
	325	----	63.5	61.0
4 Hours	20	43.0	53.0	51.2
	48	51.8	56.3	57.3
	60	52.8	58.1	60.0
	100	----	59.8	----
	200	57.0	61.2	61.8
	325	58.4	62.0	62.0
24 Hours	20	35.0	51.9	42.0
	48	40.5	57.0	47.1
	60	41.1	57.8	49.1
	100	53.0	58.0	50.4
	200	55.0	60.0	----
	325	55.8	63.8	62.5

TABLE 10: SIEVE ANALYSIS OF BEEF CATTLE WASTEWATER SOAKING TIME 24 HOURS, APPROXIMATELY 5% TS

Mesh Size of Screen	% Removal
20	44
40	47
60	50
100	58

Table 9 indicates that both soaking time as well as percent total solids of the wastewater being fractionated can have measurable effects on screen performance. These effects can be partially explained by the recognized relationship between soaking time, total solids concentration and the soluble component fraction of the solids. It can thus be rationalized that longer soaking times and low total solids concentrations are likely to encourage more of the soluble fraction to go into solution. This in turn would lead to lower percentage recovery of solids on the screen. These observations indicate a need to establish some type of a standard specifying time durations of soaking and percentage total solids when conducting tests and reporting data related to performance ratings of vibrating screen separators.

No attempt has been made to recommend any particular standard in this study. The following observations, however, can aid the eventual formulation of such standards. A soaking period of 24 hours would give more reliable and more reproducible results; it was adopted in our study primarily for this reason even though such a prolonged soaking period is certainly counter to the need for more rapid laboratory procedures. It is believed that errors inherent in sampling at low total solids concentrations may have contributed significantly to the observed effects of total solids concentration on removal efficiencies on the screen. In the low range between 1% and 5% total solids, provided that a sufficiently long soaking time has elapsed, the exclusive effect of percent total solids on percentage removal of solids should be negligible.

In Figure 7, the percentage removal $100\ (C_f - C_c)/C_f$ is plotted as a function of mesh size of screen on log-probability paper. This plot represents average estimates of screen performance obtained from laboratory sieve analysis on Tyler screens for both swine and beef cattle wastewaters. If a significant size reduction does not take place in transport as the wastewater is pumped to the screens (assumption confirmed by our experience), Figure 7 should provide accurate estimates of screen removal efficiencies within 5% of the actual value.

From the data on sieve analysis, the fineness moduli of the solids were determined to be approximately 1.57 for swine wastewater solids and 1.98 for beef cattle wastewater solids. These moduli were then used to calculate the average particle size (D_p) of the wastewater solids using the following equation given in Chemical Engineering Handbook (9)

$$D_p = 4.1 \times 10^{-3}\ (2)\ FM \qquad (12)$$

where FM = fineness modulus. From these calculations, the following values of particle size were obtained:

D_p (swine wastewater solids) = 0.012 inches

D_p (beef cattle wastewater solids) = 0.017 inches.

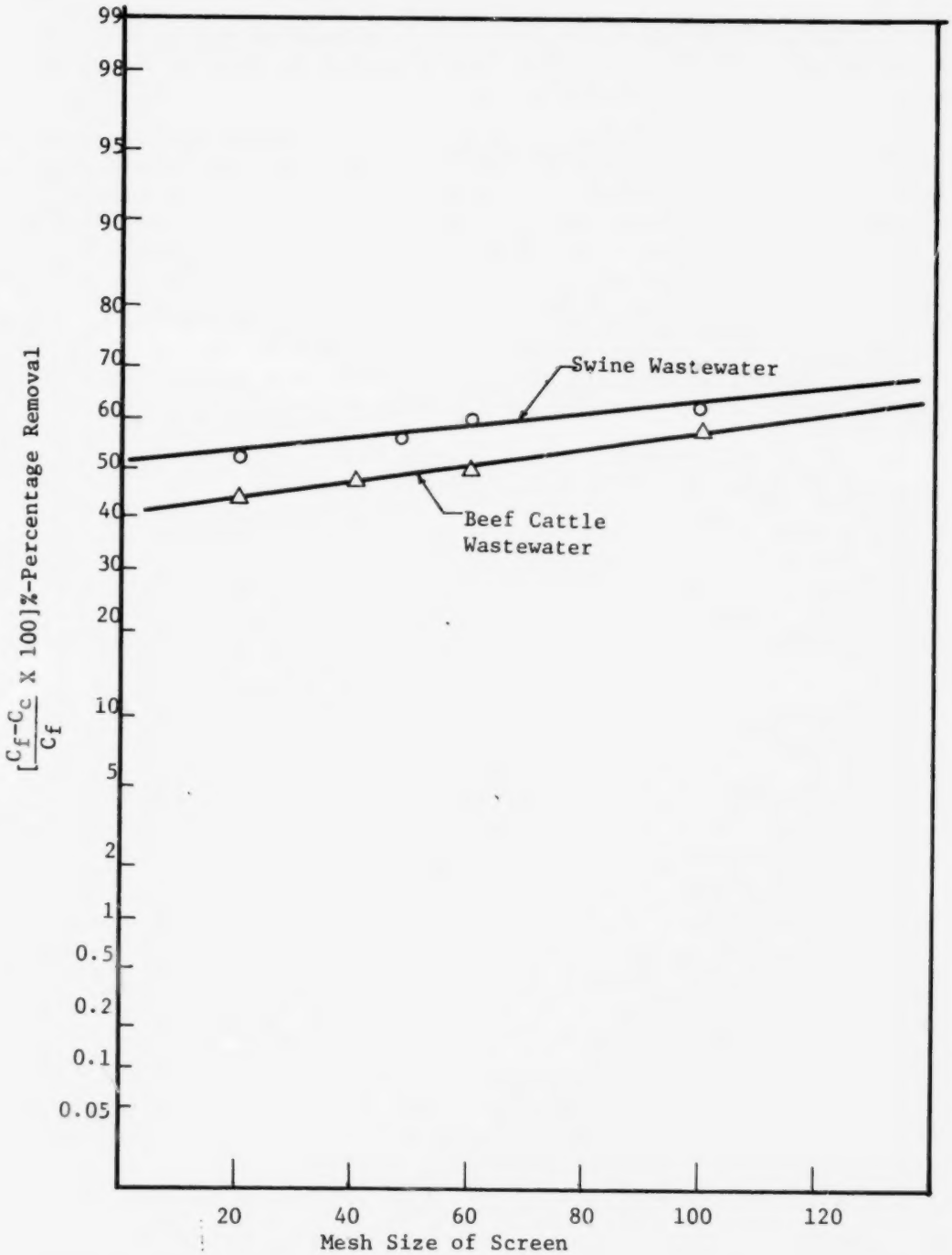


FIGURE 7: AVERAGE PERCENTAGE REMOVAL VS. MESH SIZE OF SCREEN PLOTTED ON LOG-PROBABILITY PAPER

With the average particle size thus defined, a table of the dimensionless parameter Λ [=100 $(D_p/D_s)(C_f - C_c)/C_f$] can be developed for screens tested in this study. These values are presented in Table 11 for swine wastewater and beef cattle wastewater.

2. Tests on the Vibrating Screen Separator: As was previously stated, the 18-inch model of the Sweco Vibrating Screen Separator was used to obtain all the data presented in this section. Since it is a popular separator, it is hoped that the data we obtained would be of some direct value to people who possess this brand of machine. The principle of operation of most vibrating screen machines is the same, however, irrespective of manufacturer. The basic vibrational excitation is provided by top-bottom weight assemblies mounted out of phase on an electric motor rotating at a constant angular velocity. The motor is rigidly linked to the screen assembly. Multiple drive springs (in this case, 6) link the screen assembly to a stationary base support.

The apparatus used to conduct the vibrating screen tests is shown diagrammatically in Figure 8. A close-up picture of the general setup is shown in Figure 9. In developing the test, it was essential to provide and sustain a continuous operation which would approximate actual farm conditions. The only way to do this in the lab where sample size is usually limiting is to devise a recycling system in which screened solids and effluent water from the screen are both returned on a continuous basis to a completely mixed tank from which the raw wastewater is pumped to the screen.

A 55-gallon capacity drum, D_1 in Figure 8, was used as the completely mixed chamber. Vigorous agitation of the contents of the drum was obtained by the action of a high speed impeller type mixer and the action of a bypass return flow from the main hydraulic line. Both of these operations established a satisfactory mixing pattern in the drum which approximated complete mixing. Any overflow from drum D_1 was collected by a receiving drum D_2.

A high volume constant rate sludge centrifugal pump was used. Flow regulation was achieved by the use of two gate valves V_1 and V_2 in the hydraulic line. V_2 is a bypass valve which can allow any desired fraction of the total flow to return to the mixing tank. By adjusting the two valves, it was possible to obtain a wide range of flow rates during the test. Gate valves, of course, have the disadvantage of imposing a blocking effect on the wastewater solids. For the percentage total solids level at which all the tests were run, however, the gross effect of the valves was negligible. Immediately preceding each test, maximum mixing of the chamber contents was generated by using 100% bypass in addition to the mixing impeller action.

The continuous return of the solid and liquid fractions from the screen to the mixing chamber permitted each test to be run for any desired time duration. The return of these solid and liquid fractions was interrupted only for short periods of time during which cake flow and centrate flow measurements were made.

TABLE 11: VALUES OF $\Lambda = (\frac{C_f - C_c}{C_f} \times 100) \frac{D_p}{D_s}$ AS USED IN THIS STUDY

(a) Swine Wastewater

Mesh size of screen	50	74	100	120	200	230
D_s (in.)	.0116	.0074	.0058	.0049	.0029	.0026
D_p (in.)	.012	.012	.012	.012	.012	.012
$R = \frac{C_f - C_c}{C_f} \times 100$ (Figure 7)	55	60	64	56	70*	70*
$R\ (\frac{D_p}{D_s}) = \Lambda$	62	105	144	175	290	307

(b) Beef Cattle Wastewater

Mesh size of screen	50	74	100	120	200	230
D_s (in.)	.0116	.0074	.0058	.0049	.0029	.0026
D_p (in.)	.017	.017	.017	.017	.017	.017
$R = \frac{C_f - C_c}{C_f} \times 100$ (Figure 7)	45	52	58	62	70*	70*
$R\ (\frac{D_p}{D_s}) = \Lambda$	66	120	170	215	410	457

*70% removal is assumed to be maximum possible.

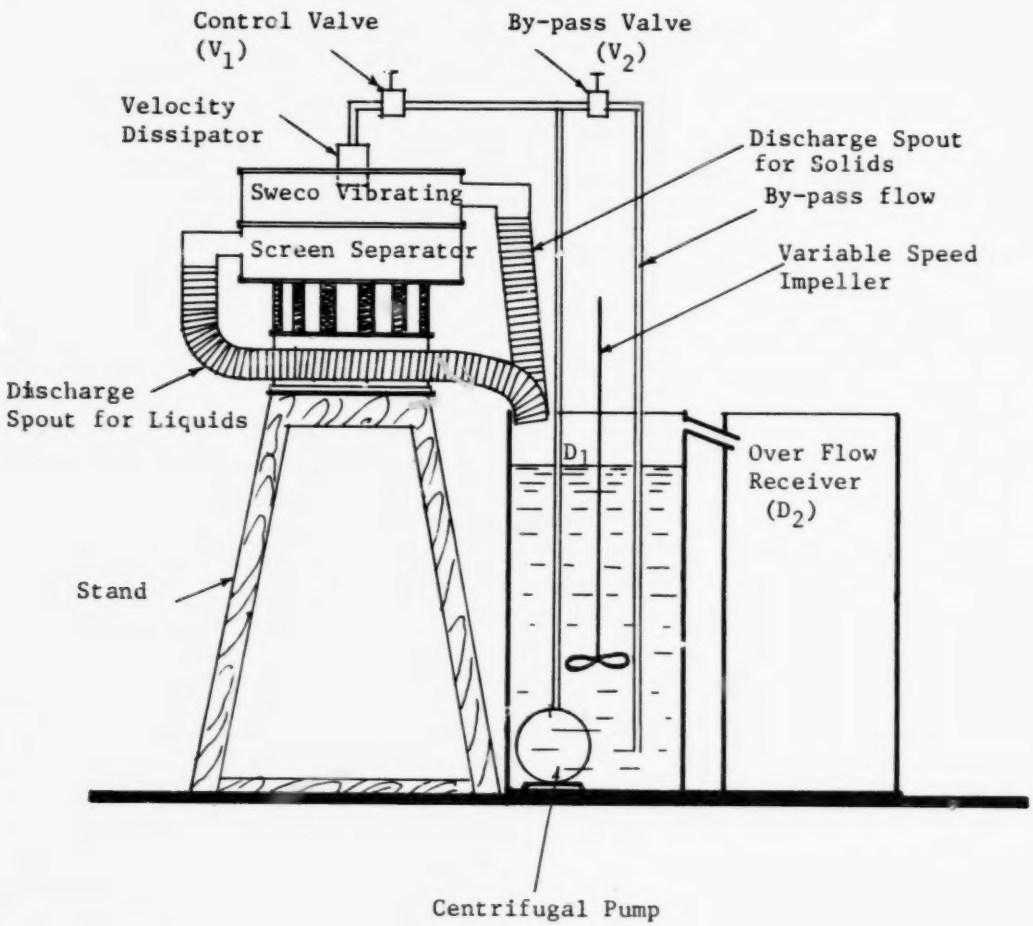


FIGURE 8: SCHEMATIC OF EXPERIMENTAL APPARATUS FOR VIBRATING SCREEN TESTS

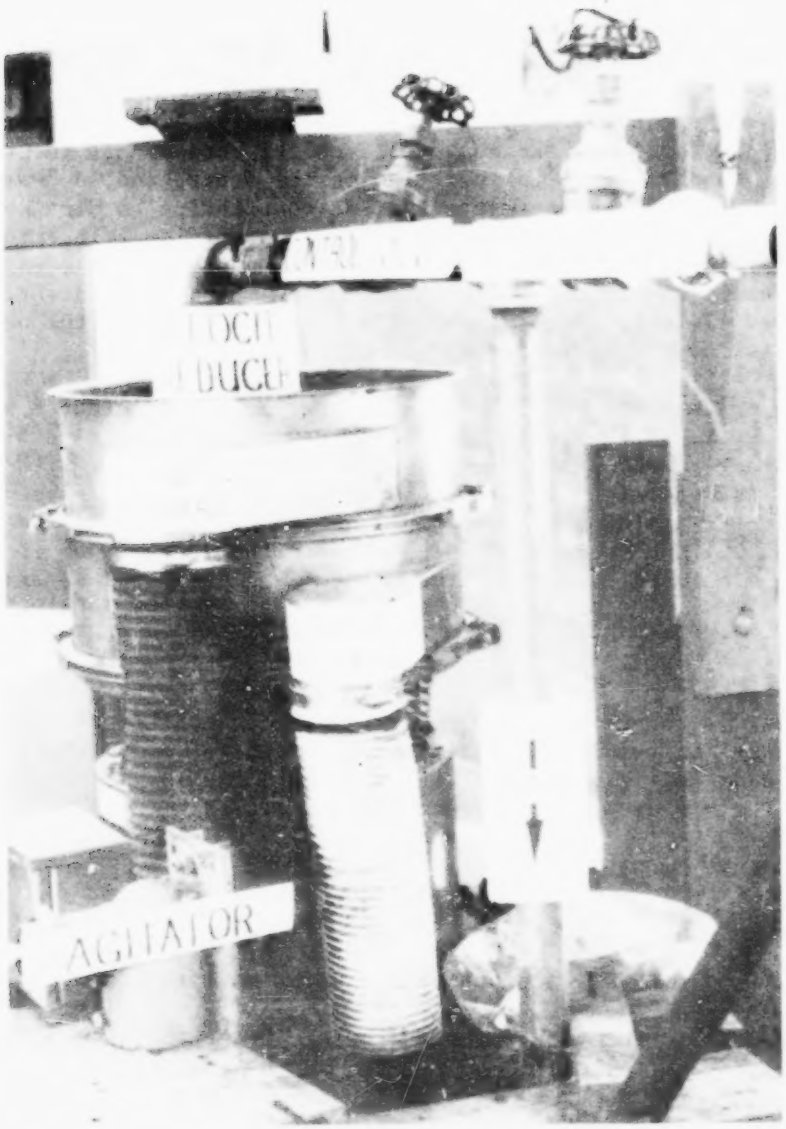


FIGURE 9: CLOSE-UP VIEW OF SETUP FOR SCREEN TEST

In a typical test, the desired machine variables (screen size, top-bottom weight ratio, lead angle between top and bottom weight assemblies) were first established. Maximum mixing of the wastewater in the tank was then established. The flow of wastewater to the screen was regulated until an approximate steady state condition was observed on the screen. This equilibrium condition is defined by very characteristic patterns of motion on the screen. This motion maintains a steady flow of "roped", dewatered, and "balled" solids via the periphery of the screen to the discharge spout. For a given set of machine variables, there is only one flow rate (Q) of feed at which equilibrium can be observed. If the rate of feed is below this value, the solids tend to crowd at the center. Their movement becomes so sluggish that inordinately high residence times are obtained for the average particle on the screen. If the rate of feed is higher than the equilibrium value on the other hand, a "wash out" of the screen solids occurs instantly. At equilibrium, a distinctive pattern emerges. Measurements of the cake rate of flow, $\alpha(lb_m/min)$, and the centrate rate of flow, Q(gal./min), are taken only under equilibrium conditions as specified above. α and Q are measured by diverting their respective flows to appropriate collectors and clocking the accumulation of material over time intervals of about one minute.

Both the drive motor of the screen and the pump are actuated by a common electric switch. The instantaneous average mass of cake retained on the screen under steady state condition has been designated $\beta\,(lb_m)$. This quantity is determined by simultaneously shutting-off the pump and screen during steady state operation, blocking the exit spout at the same time and measuring the residual mass of cake on the screen when it ceases to vibrate. The mean residence time, τ(sec), is then defined as:

$$\tau(\text{sec}) = \frac{\beta\ (lb_m)}{\alpha\ (lb_m/\text{sec})} = \frac{\text{instantaneous average mass of cake retained on screen}}{\text{average mass velocity of cake on the screen}}$$

In Table 12 a complete set of experimental data obtained from vibratory screen tests on swine wastewater has been tabulated. A similar set of data on beef cattle wastewater is given in Table 13. In each of these tables, the raw data are given as the quantities:

Q (gal./min) = total flow rate of feed

$\alpha\ (lb_m/min)$ = mass velocity of cake on screen

$\beta\ (lb_m)$ = instantaneous mass of cake retained on screen.

From these basic quantities the following parameters are synthesized:

$q = \frac{Q}{A\xi}\ (\frac{ft}{sec})$ = feed rate of flow per unit area of screen open space. It represents the average velocity through screen opening. It is used to define the modified Reynolds number.

TABLE 12a: RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON SWINE WASTEWATER.
Mesh Size of Screen = #50. % Total Solids of Wastewater = 1.4%-2%.

A = 1.02 ft^2, μc = 0.0672 lb_m/ft-sec, D_s = .0012 ft, ξ = .526

	ϕ = Lead Angle	0°	15°	30°	45°	60°	75°	90°
$\frac{W_b}{W_t}$ = 2.56	Q (gal/min)		31.15	31.15	28.75			
	α=cake flow (lb/min)		2.85	4.2	4.6			
	β=cake retained (lb_m)		3.8	1.8	1.8			
	$q=Q/A\xi$ (ft/sec)(10^{-1})		1.29	1.29	1.19			
	$\tau=\beta/\alpha$ X 60 (sec)		80.0	25.7	23.5			
	$q\tau/D_s$ X (10^3)		8.624	2.77	2.338			
	$N_{Re}=qD_s\rho_c/\mu c$ X (10^{-3})		2.31	2.31	2.13			
$\frac{W_b}{W_t}$ = 2.92	Q		25.16	35.94				
	α		4.8	6.45				
	β		2.1	1.5				
	q X 10^{-1}		1.04	1.49				
	τ		26.2	13.9				
	$q\tau/D_s$ X 10^3		2.281	1.729				
	N_{Re} X 10^{-3}		1.87	2.67				
$\frac{W_b}{W_t}$ = 3.46	Q		31.15	35.94	35.94			
	α		4.7	5.9	6.9			
	β		2.4	1.7	2.3			
	q X 10^{-1}		1.29	1.49	1.49			
	τ		30.6	17.3	20.0			
	$q\tau/D_s$ X 10^3		3.229	2.152	2.487			
	N_{Re} X 10^{-3}		2.31	2.67	2.67			
$\frac{W_b}{W_t}$ = 3.83	Q		23.02	35.94				
	α		5.1	5.4				
	β		1.9	2.1				
	q X 10^{-1}		.956	1.49				
	τ		22.3	23.3				
	$q\tau/D_s$ X 10^3		1.776	2.898				
	N_{Re} X 10^{-3}		1.71	2.67				

TABLE 12b: RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON SWINE WASTEWATER. Mesh Size of Screen = #74. % Total Solids of Wastewater = 1.4%-2%.

$A = 1.02\ ft^2$, $\mu c = 0.0672\ lb_m/ft\text{-}sec$, $D_s = 8.17 \times 10^{-4}\ ft$, $\xi = .52$

$\frac{W_b}{W_t}$	ϕ = Lead Angle	0°	15°	30°	45°	60°	75°	90°
= 2.5	Q (gal/min)	7.19	12.2	18.7	22.3	19.4	24.4	24.4
	α=cake flow (lb/min)	2.0	2.8	4.4	7.7	7.6	5.2	7.2
	β=cake retained (lb_m)	7.0	7.4	7.1	3.6	2.7	2.7	6.0
	$q=Q/A\xi$ (ft/sec) (10^{-1})	.302	.512	.786	.937	.815	1.02	1.02
	$\tau=\beta/\alpha \times 60$ (sec)	210.0	158.6	96.8	28.0	21.3	31.2	50.0
	$q\tau/D_s \times (10^3)$	7.763	9.948	9.307	3.21	2.125	3.914	6.273
	$N_{Re}=qD_s\rho_c/\mu c \times (10^{-3})$	.367	.623	.955	1.139	.991	1.246	1.246

$\frac{W_b}{W_t}$								
= 2.77	Q	16.5	16.5	19.4	20.1	21.6	21.6	27.3
	α	6.0	5.6	6.5	6.9	7.5	7.0	8.5
	β	5.0	4.6	2.8	2.6	3.1	3.5	4.9
	$q \times 10^{-1}$	.69	.693	.815	.844	.907	.907	1.15
	τ	50.0	49.3	25.8	22.6	24.8	30.0	34.6
	$q\tau/D_s \times 10^3$	4.242	4.182	2.573	2.336	2.754	3.332	4.857
	$N_{Re} \times 10^{-3}$	.843	.843	.991	1.026	1.103	1.103	1.394

$\frac{W_b}{W_t}$								
= 3.16	Q	15.8	18.7	18.7	24.4	31.6	27.3	15.8
	α	5.5	5.1	6.2	7.6	9.4	7.9	8.1
	β	5.6	6.0	2.4	3.0	3.5	4.8	5.6
	$q \times 10^{-1}$	.66	.786	.786	1.02	1.327	1.147	.66
	τ	61.1	70.6	23.2	23.7	22.3	36.4	41.5
	$q\tau/D_s \times 10^3$	4.963	6.788	2.231	2.973	3.623	5.109	3.371
	$N_{Re} \times 10^{-3}$	.807	.955	.955	1.25	1.61	1.39	.807

$\frac{W_b}{W_t}$								
= 3.77	Q	15.81	21.6	25.9	30.2	30.2	30.2	23.0
	α	5.5	7.6	9.5	11.0	11.2	11.1	5.0
	β	4.3	2.3	2.8	3.7	3.3	5.3	5.5
	$q \times 10^{-1}$	.664	.907	1.09	1.27	1.27	1.27	.966
	τ	46.9	18.2	17.7	20.2	17.7	28.6	66.0
	$q\tau/D_s \times 10^3$	3.812	2.021	2.357	3.136	2.748	4.441	7.805
	$N_{Re} \times 10^{-3}$	.807	1.103	1.323	1.542	1.542	1.542	1.175

TABLE 12c: RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON SWINE WASTEWATER. Mesh Size of Screen = #120. % Total Solids of Wastewater = 1.4%-2%.

$A = 1.02\ ft^2$, $\mu c = 0.0672\ lb_m/ft\text{-}sec$, $D_s = 4.83 \times 10^{-4}\ ft$, $\xi = 0.473$

	ϕ = Lead Angle	0°	15°	30°	45°	60°	75°	90°
$\frac{W_b}{W_t}$ = 2.56	Q (gal/min)		20.8	34.7	34.7	33.1	31.1	31.1
	α=cake flow (lb/min)		2.4	5.7	5.5	5.6	3.6	3.6
	β=cake retained (^{lb_m})		3.5	4.0	2.7	4.0	4.0	4.4
	$q=Q/A\xi$ (ft/sec)(10^{-1})		.961	1.60	1.60	1.53	1.44	1.44
	$\tau=\beta/\alpha$ X 60 (sec)		87.5	42.1	29.4	42.9	66.7	73.3
	$q\tau/D_s$ X (10^3)		17.401	13.967	9.754	13.577	19.833	21.796
	$N_{Re}=qD_s\rho_c/\mu c$ X (10^{-3})		.69	1.15	1.15	1.09	1.03	1.03
$\frac{W_b}{W_t}$ = 2.92	Q		22.8	34.7	35.9	35.9	26.4	26.4
	α		4.5	5.4	8.4	7.2	4.0	3.6
	β		3.7	3.5	2.9	3.5	2.6	3.5
	q X 10^{-1}		1.05	1.602	1.658	1.658	1.219	1.219
	τ		49.3	38.9	20.7	29.2	39.0	58.3
	$q\tau/D_s$ X 10^3		10.747	12.906	7.105	10.023	9.844	14.716
	N_{Re} X 10^{-3}		.757	1.15	1.19	1.19	.877	.877
$\frac{W_b}{W_t}$ = 3.46	Q		21.56	33.54	31.15	29.95	31.63	32.35
	α		1.0	2.4	7.6	5.2	4.8	3.6
	β		2.0	2.4	2.8	3.3	3.8	5.6
	q X 10^{-1}		.996	1.55	1.439	1.383	1.461	1.49
	τ		120.0	60.0	22.1	38.1	47.5	93.3
	$q\tau/D_s$ X 10^3		24.736	19.241	6.582	10.910	14.365	28.858
	N_{Re} X 10^{-3}		.715	1.113	1.03	.994	1.05	1.07
$\frac{W_b}{W_t}$ = 3.83	Q		20.4	26.4	24.0	30.0	31.1	28.8
	α		3.7	3.1	3.4	3.3	5.8	4.0
	β		2.6	2.3	2.2	2.7	4.1	5.2
	q X 10^{-1}		.942	1.219	1.108	1.385	1.436	1.330
	τ		42.2	44.5	38.8	49.1	42.4	78.0
	$q\tau/D_s$ X 10^3		8.231	11.232	8.903	14.083	12.608	21.478
	N_{Re} X 10^{-3}		.677	.876	.797	.996	1.032	.956

TABLE 12d: RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON SWINE WASTEWATER.
Mesh Size of Screen = #200. % Total Solids of Wastewater = 1.4%-2%.

$A = 1.02\ ft^2$, $\mu c = 0.0672\ lb_m/ft\text{-}sec$, $D_s = .000242\ ft^2$, $\xi = .34$

	ϕ = Lead Angle	0°	15°	30°	45°	60°	75°	90°
$\frac{W_b}{W_t}$ = 2.5	Q (gal/min)		5.75	7.188	6.47			
	α=cake flow (lb/min)		1.9	2.5	2.6			
	β=cake retained (lb_m)		5.1	2.5	3.2			
	$q=Q/A\xi$ (ft/sec)(10^{-1})		.369	.462	.415			
	$\tau=\beta/\alpha$ X 60 (sec)		161	60	73.8			
	$q\tau/D_s$ X (10^3)		24.576	11.449	12.676			
	$N_{Re}=qD_s\rho c/\mu c$ X (10^{-3})		.133	.166	.149			

$\frac{W_b}{W_t}$ = 3.16	Q		10.78	11.5	10.78	8.57		
	α		5.9	5.9	4.9	2.9		
	β		2.2	3.0	3.6	5.2		
	q X 10^{-1}		.692	.739	- .692	.551		
	τ		22.4	30.5	44.08	107.6		
	$q\tau/D_s$ X 10^3		6.410	9.311	12.615	24.480		
	N_{Re} X 10^{-3}		.249	.266	.249	.198		

$\frac{W_b}{W_t}$ = 3.83	Q	3.59	11.5	5.75	6.47			
	α	2.1	5.3	2.6	3.2			
	β	2.4	1.7	2.6	3.6			
	q X 10^{-1}	.231	.739	.369	.416			
	τ	68.6	19.25	60.0	67.5			
	$q\tau/D_s$ X 10^3	6.538	5.877	9.158	11.594			
	N_{Re} X 10^{-3}	.0803	.266	.133	.149			

TABLE 12e: RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON SWINE WASTEWATER.
Mesh Size of Screen = #230. % Total Solids of Wastewater = 1.4%-2%.

$A = 1.02\ ft^2$, $\mu c = 0.0672\ lb_m/ft\text{-}sec$, $D_s = 2.42 \times 10^{-4}\ ft$, $\xi = .46$

	ϕ = Lead Angle	0°	15°	30°	45°	60°	75°	90°
$\frac{W_b}{W_t}$ = 2.5	Q (gal/min)		7.2	5.8				
	α=cake flow (lb/min)		2.0	1.0				
	β=cake retained (lb_m)		2.9	1.0				
	$q=Q/A\xi$ (ft/sec)(10^{-1})		.342	.275				
	$\tau=\beta/\alpha$ X 60 (sec)		87.0	144.0				
	$q\tau/D_s$ X (10^3)		12.291	16.388				
	$N_{Re}=qD_s\rho_c/\mu c$ X (10^{-3})		1.23	.991				
$\frac{W_b}{W_t}$ = 2.92	Q		3.6	10.1	11.5			
	α		1.0	1.5	1.8			
	β		.8	2.0	2.2			
	q X 10^{-1}		.171	.48	.546			
	τ		48.0	80.0	73.3			
	$q\tau/D_s$ X 10^3		3.391	15.85	16.54			
	N_{Re} X 10^{-3}		.6145	1.726	1.97			
$\frac{W_b}{W_t}$ = 3.46	Q		7.9	8.6	11.5			
	α		2.4	2.6	2.4			
	β		1.9	1.2	2.7			
	q X 10^{-1}		.375	.408	.546			
	τ		47.2	27.7	67.5			
	$q\tau/D_s$ X 10^3		7.363	4.874	15.231			
	N_{Re} X 10^{-3}		1.35	1.47	1.97			
$\frac{W_b}{W_t}$ = 3.83	Q		2.9	7.2	8.6			
	α		.8	.9	1.0			
	β		.9	2.2	2.2			
	q X 10^{-1}		.138	.342	.408			
	τ		67.5	146.7	132.0			
	$q\tau/D_s$ X 10^3		3.841	20.725	22.275			
	N_{Re} X 10^{-3}		.495	1.23	1.47			

TABLE 13a: RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON BEEF CATTLE WASTEWATER
Mesh Size of Screen = #74. % Total Solids of Test Wastewater = 2%.

$A = 1.02\ ft^2$, $D_s = 8.17 \times 10^{-4}$ ft, $\xi = .52$, $\mu = 6.72 \times 10^{-2}\ lb_m/ft\text{-}sec$

	ϕ = Lead Angle	0°	15°	30°	45°	60°	75°	90°
$\frac{W_b}{W_t}$ = 2.56	Q (gal/min)				17.25	18.69	10.06	11.50
	α=cake flow (lb/min)				8.1	11.1	5.9	3.6
	β=cake retained (lb_m)				5.0	5.2	5.2	7.2
	$q=Q/A\xi$ (ft/sec)(10^{-1})				.725	.785	.423	.483
	$\tau=\beta/\alpha \times 60$ (sec)				37.0	28.2	52.9	120.0
	$q\tau/D_s \times (10^3)$				3.282	2.710	2.736	7.095
	$N_{Re}=qD_s\rho_c/\mu_c \times (10^{-3})$				.881	.954	.514	.587
$\frac{W_b}{W_t}$ = 2.92	Q			11.5	15.09	15.81	15.81	11.50
	α			5.8	8.6	9.7	10.1	5.7
	β			6.6	4.0	4.6	4.7	5.5
	$q \times 10^{-1}$			.483	.634	.664	.664	.483
	τ			68.3	27.9	28.5	27.9	57.9
	$q\tau/D_s \times 10^3$			4.038	2.165	2.317	2.268	2.423
	$N_{Re} \times 10^{-3}$			.587	.771	.807	.807	.587
$\frac{W_b}{W_t}$ = 3.46	Q			8.63	7.19	21.56	17.25	10.78
	α			5.6	6.4	17.4	10.0	6.2
	β			2.5	5.3	6.1	6.1	5.9
	$q \times 10^{-1}$			.363	.302	.906	.724	.453
	τ			26.8	56.8	21.0	36.6	57.1
	$q\tau/D_s \times 10^3$			1.189	2.100	2.328	3.246	3.165
	$N_{Re} \times 10^{-3}$			.441	.367	1.101	.881	.550
$\frac{W_b}{W_t}$ = 3.83	Q				10.06	19.17	16.53	11.50
	α				6.4	10.1	8.0	7.2
	β				3.9	6.4	5.9	6.8
	$q \times 10^{-1}$				.423	.805	.694	.483
	τ				36.6	38.0	44.3	56.7
	$q\tau/D_s \times 10^3$				1.893	3.745	3.765	3.352
	$N_{Re} \times 10^{-3}$				.514	.979	.844	.587

TABLE 13b: RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON BEEF CATTLE WASTEWATER. Mesh Size of Screen = #74. % Total Solids of Test Wastewater = 1.3%.

$A = 1.02\ ft^2$, $D_s = 8.17 \times 10^{-4}$ ft, $\xi = .52$, $\mu = 6.72 \times 10^{-2}\ lb_m/ft\text{-}sec$

	ϕ = Lead Angle	0°	15°	30°	45°	60°	75°	
$\frac{W_b}{W_t}$ = 2.56	Q (gal/min)				17.97	17.97	15.81	11.5
	α=cake flow (lb/min)				6.6	6.7	5.4	6.5
	β=cake retained (lb_m)				4.7	3.9	3.6	11.9
	$q=Q/A\,\xi$ (ft/sec) (10^{-1})				.755	.755	.664	.483
	$\tau=\beta/\alpha \times 60$ (sec)				42.7	34.9	40.0	45.2
	$\tau/D_s \times (10^3)$				3.945	3.225	3.251	2.673
	$N_{Re}=qD_s\rho_c/\mu_c \times (10^{-3})$				.918	.918	.807	.587

TABLE 13c: Mesh Size of Screen = #120. % Total Solids of Test Wastewater = 2%.

$A = 1.02\ ft^2$, $D_s = 4.83 \times 10^{-4}$ ft, $\xi = .473$, $\mu_c = 6.72 \times 10^{-2}\ lb_m/ft\text{-}sec$.

	ϕ = Lead Angle	0°	15°	30°	45°	60°	75°	90°
$\frac{W_b}{W_t}$ = 2.56	Q				4.31			
	α				3.9			
	β				2.4			
	$q \times 10^{-1}$				.199			
	τ				36.9			
	$q\tau/D_s \times 10^3$				1.521			
	$N_{Re} \times 10^{-3}$				.143			

TABLE 13d: RESULTS OF VIBRATING SCREEN SEPARATOR TEST ON BEEF CATTLE WASTEWATER. Mesh Size of Screen = #50. % Total Solids of Test Wastewater = 2%.

$A = 1.02\ ft^2$, $D_s = .00121$ ft, $\xi = .526$, $\mu c = .0672\ lb_m/ft\text{-}sec$

	ϕ = Lead Angle	0°	15°	30°	45°	60°	75°	90°
$\frac{W_b}{W_t}$ = 3.83	Q		6.47					
	α		4.9					
	β		3.5					
	$q \times 10^{-1}$		.268					
	τ		42.9					
	$q\tau/D_s \times 10^3$		.9526					
	$N_{Re} \times 10^{-3}$		.484					

$\frac{W_b}{W_t}$ = 3.46	Q		5.75					
	α		4.3					
	β		2.7					
	$q \times 10^{-1}$		.239					
	τ		37.67					
	$q\tau/D_s \times 10^3$		.743					
	$N_{Re} \times 10^{-3}$		.430					

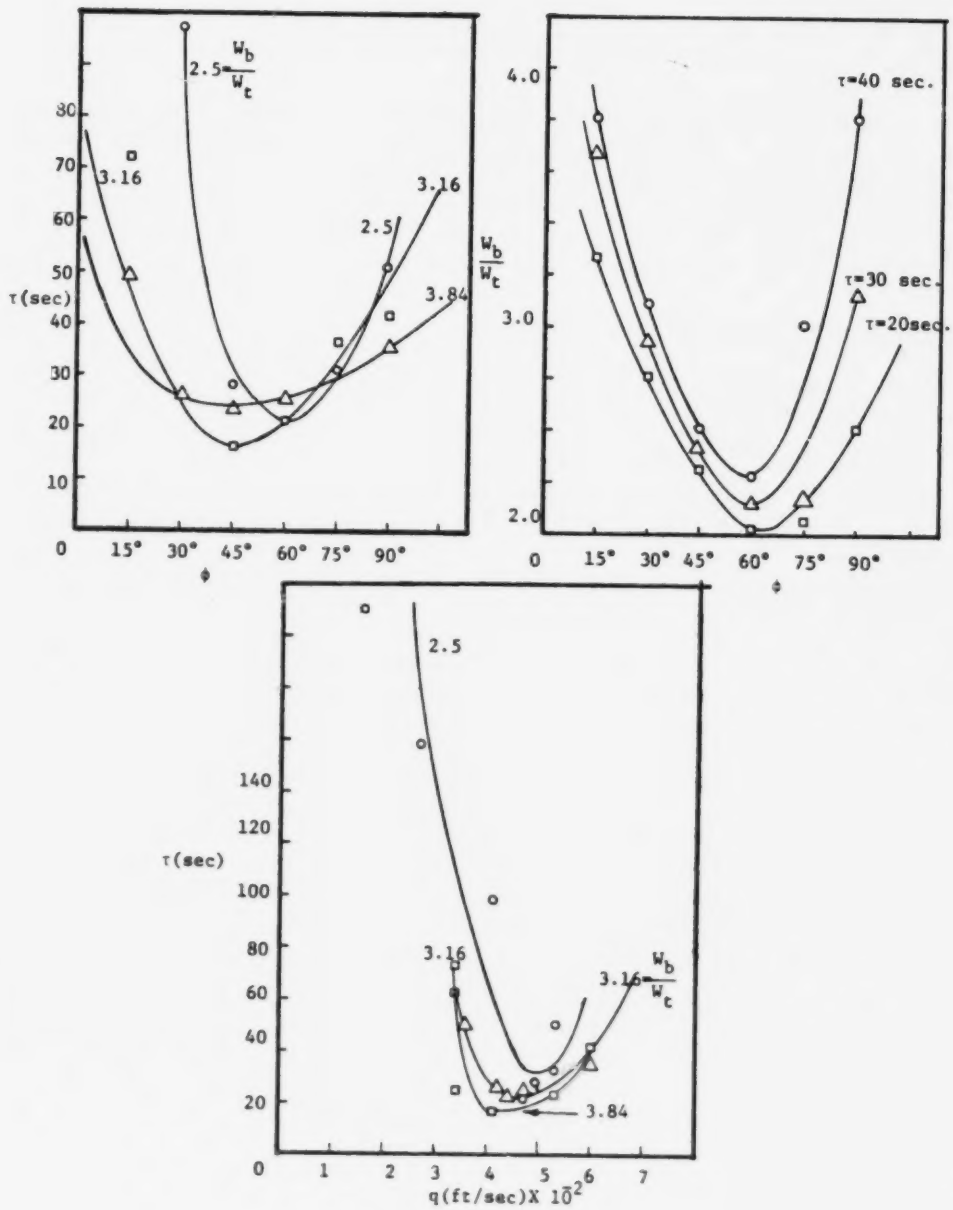


FIGURE 10: ALTERNATIVE PLOTS OF THE SCREEN TEST DATA ON SWINE WASTE-WATER

$\tau = \frac{\beta}{\alpha} \times 60$ (sec) = Mean residence time.

$\frac{q\tau}{D_s}$ = Dimensionless residence time.

$N_{Re} = \frac{q\rho_c D_s}{\mu c}$ = Modified Reynold's number.

The centrate absolute viscosity μ_c is taken as 6.72×10^{-2} (lb$_m$/ft-sec) in all calculations. This is the best estimate obtained from the recent data of Kumar, Bartlett and Mohsenin (10). Blanks in the tables imply that it was not possible to achieve equilibrium performance for the specified variables. We shall now discuss the results of tests for swine wastewater and beef cattle wastewater individually.

Test Results for Swine Wastewater:

The most complete data were obtained for mesh sizes #74 and #120. Equilibrium machine performance was achieved at practically all combinations of machine variables tested. In Figure 10, the data in Table 12b corresponding to the test on #74 screen, were plotted in a variety of forms. Each plot shows very distinctive minima irrespective of the variables of the plot. It is clear that a large number of plots of this type is possible. The dimensionless form of the same plot can be seen in Figure 5 which is a graphical representation of the data in Tables 12b and c corresponding respectively to tests on screens #74 and #120. The plot in Figure 5 is obviously more concise, inclusive of the primary factors and thus to a large degree, very comprehensive. Decisions concerning optimum performance conditions made on the basis of this plot would have taken a good number of the pertinent variables into consideration. Consequently such decisions are to be preferred to those deduced from a less comprehensive representation on the experimental data.

It is observed that the remaining tables of the swine wastewater screen test, namely Tables 12a, d and e, do not provide a sufficient number of data points to facilitate optimization plots similar to Figure 5 for screen sizes #50, #200, and #230. However, it is still possible to pick optimum residence time values by inspection of the tables. In Figure 6, all the data in Table 12 have been combined with those in Table 11 to obtain dimensionless performance curves for vibrating screen separation of swine wastewater solids. We shall now illustrate the practical use of these curves.

Illustrative Example:

A livestock producer operating a 1000-hog confinement unit proposes to install a vibrating screen separator as a first step in a wastewater management scheme involving biological treatment in an aerated lagoon and recycling of the treated wastewater for flushing purposes in the confined building. What size of vibrating screen separator does he need?

At what machine variables must he run the unit to obtain optimum performance?

Solution:

Assume that each hog produces an average of 1.5 gallons of manure (urine + feces) daily. For transport and flushing purposes, we assume that each unit volume of manure is diluted ten times in the flush water. Each hog has consequently a gross total of 15 gallons of wastewater which must be screened daily. Since there are 1000 hogs, we must therefore handle 15,000 gallons of water daily through the machine. If we assume that this machine operates on the average 10 hours/day, we are then looking for a 25 gpm capacity machine.

We desire a solid removal efficiency of at least 50% on the screen. From Figure 7 and Table 11a, screen mesh size #74 has an average removal efficiency of 60% (>50% OK). Therefore we select a #74 mesh size of screen.

For #74 mesh size of screen, Figure 5 indicates optimum dimensionless residence time $(q\tau/D_s)$ optimum = 1.5×10^3.

This optimum value occurs when the machine variables are:

ϕ (Lead angle between top and bottom weights) = 30° to 45°

W_b/W_t (Bottom-top weight ratio) = 3.16

From Table 11a, screen #74 has $\Lambda = 100\ (D_p/D_s)(C_f - C_c)/C_f = 105$

From Figure 6:

$(q\tau/D_s)$ optimum = 1500 <=> $N_{Re} = q\rho_c D_s/\mu_c = 0.06$

$\Lambda_{\#74} = 105$

$\rho_c \cong 62.4\ lb_m/ft^3$

$D_s \cong 8.17 \times 10^{-4}\ ft$

$\mu_c \cong 6.72 \times 10^{-2}\ lb_m/ft\text{-}sec$

$$q = \frac{6 \times 10^{-2}\ \mu_c}{\rho_c\ D_s} = \frac{(6 \times 10^{-2})(6.72 \times 10^{-2})}{(62.4)(8.17 \times 10^{-4})}\ (ft/sec)$$

$q \cong 8 \times 10^{-2}\ (ft/sec)$

for a screen of % opening 52.6%, $\xi = 0.526$

$$q = \frac{Q}{A\xi};\ \frac{Q}{A} = q\xi = (8 \times 10^{-2})(.526) = 4.5 \times 10^{-2}\ (ft^3/ft^2\text{-}sec)$$

$$\frac{Q}{A} = \frac{\text{flow rate}}{\text{unit surface area of screen}}$$

$$= 4.5 \times 10^{-2} \left(\frac{ft^3}{ft^2\text{-sec}}\right) \times 60 \text{ (sec/min)} = 2.7 \frac{ft^3}{ft^2\text{-min}}$$

$$= 2.7 \left(\frac{ft^3}{ft^2\text{-min}}\right) \times 7.5 \text{ (gal/ft}^3) \simeq \frac{20 \text{ gallons}}{(\text{min})(ft^2)}$$

The 18-inch diameter model of Sweco Vibrating Screen Separator has an effective surface area,

$$A \simeq 1.02 \text{ ft}^2$$

$$Q = \frac{20 \text{ gallons}}{(\text{min})(ft^2)} \times 1.02 \text{ ft}^2 \simeq \frac{20 \text{ gallons}}{\text{min}}$$

This is less than the 25 gallons/min which we need. However, if we let the machine run for 13 hours instead of 10 hours a day we have,

$$(Q)_{\text{needed}} = \frac{15{,}000 \text{ gallons}}{13 \times 60 \text{ (min)}} \simeq \frac{19 \text{ gallons}}{\text{min}}$$

which then makes it possible for this machine to be used.

Alternatively we can specify a 24 inch diameter screen of effective area

$$A \simeq 2.2 \text{ ft}^2, \quad Q = \frac{20 \text{ (gallons)}}{(ft^2\text{-min})} \times 2.2 \text{ ft}^2 = \frac{44 \text{ gallon}}{\text{min}}$$

which is far in excess of the 25 gallons/min required.

Design Summary:

(i) Machine Specifications: Either (a) Sweco Vibrating Screen Separator Model 24-inch operating for 10 hours per day (estimated cost = $1,500, 1 hp) or (b) Sweco Vibrating Screen Separator Model 18-inch operating 13 hours per day (estimated cost - $1,000, 1 hp).

(ii) Machine Variables:

ϕ = 30° to 45°

$W_b/W_t = 3.16$

(iii) Process Variables (expected):

$$R = \frac{C_f - C_c}{C_f} \simeq 60\%$$

Q = 20 or 44 gallons/min

D_p = 0.012 inches

A somewhat different plot of the data is represented in Figure 11. This plot is basically the same as that of Figure 6 except that in Figure 11, the performance parameter Λ is plotted against Reynolds number (N_{Re}) with the dimensionless residence time ($q\tau/D_s$) as a parameter. It is felt that there may be circumstances under which the form in Figure 11 would be found more convenient. The matter of convenience aside, the plot in the form of Figure 11 shows an interesting feature which was not as well defined in Figure 6. This is the apparent existence of a common point of convergence. The practical implication of this is that the Reynolds Number N_{Re} = 0.04 represents a unique solution where the removal efficiency is the same irrespective of screen size and residence time. The full implication of this from the standpoint of machine operation is unclear and deserves more attention and study than we have been able to give it.

Test Results for Beef Cattle Wastewater:

As is apparent from Table 13 we were able to obtain the most complete set of results from screen size #74. Repeated attempts convinced us that the fibrous characteristics of the beef cattle solids (cake) appeared to agree best with this mesh size of screen. Mesh sizes below (represented by #50 screen, Table 13d) and mesh sizes above (represented by #120 screen, Table 13c) performed comparatively poorly and at best, showed in each case only one set of variables at which equilibrium was attainable. This observation permits us to recommend #74 screen categorically as the most suitable as far as beef cattle wastewater is concerned.

An optimization plot identical to Figure 5 is developed from Table 13a and represented as Figure 12. In this case the optimum dimensionless residence time ($q\tau/D_s$) optimum is 1200 and corresponds to machine variables:

ϕ = 30° and W_b/W_t = 3.46.

A screen performance curve similar to Figure 6 is developed for beef cattle wastewater and represented as Figure 13.

Exploratory Investigation of Granular Filters:

A number of different kinds of granular filters have been used for the purification of water and the treatment of domestic and industrial wastewaters (11). There does not exist to our knowledge a reported instance in which this method has been explored for the removal of solids from livestock wastewater. In the agonizing process of searching for low cost methods for solids removal from animal wastewater, it was felt that, the associated plug-up problems aside, filtration of screened livestock wastewater through shallow beds of silica sand or finely divided anthracite can provide a possible answer to the basic problem of solids removal at low cost. This section of the report will deal briefly with

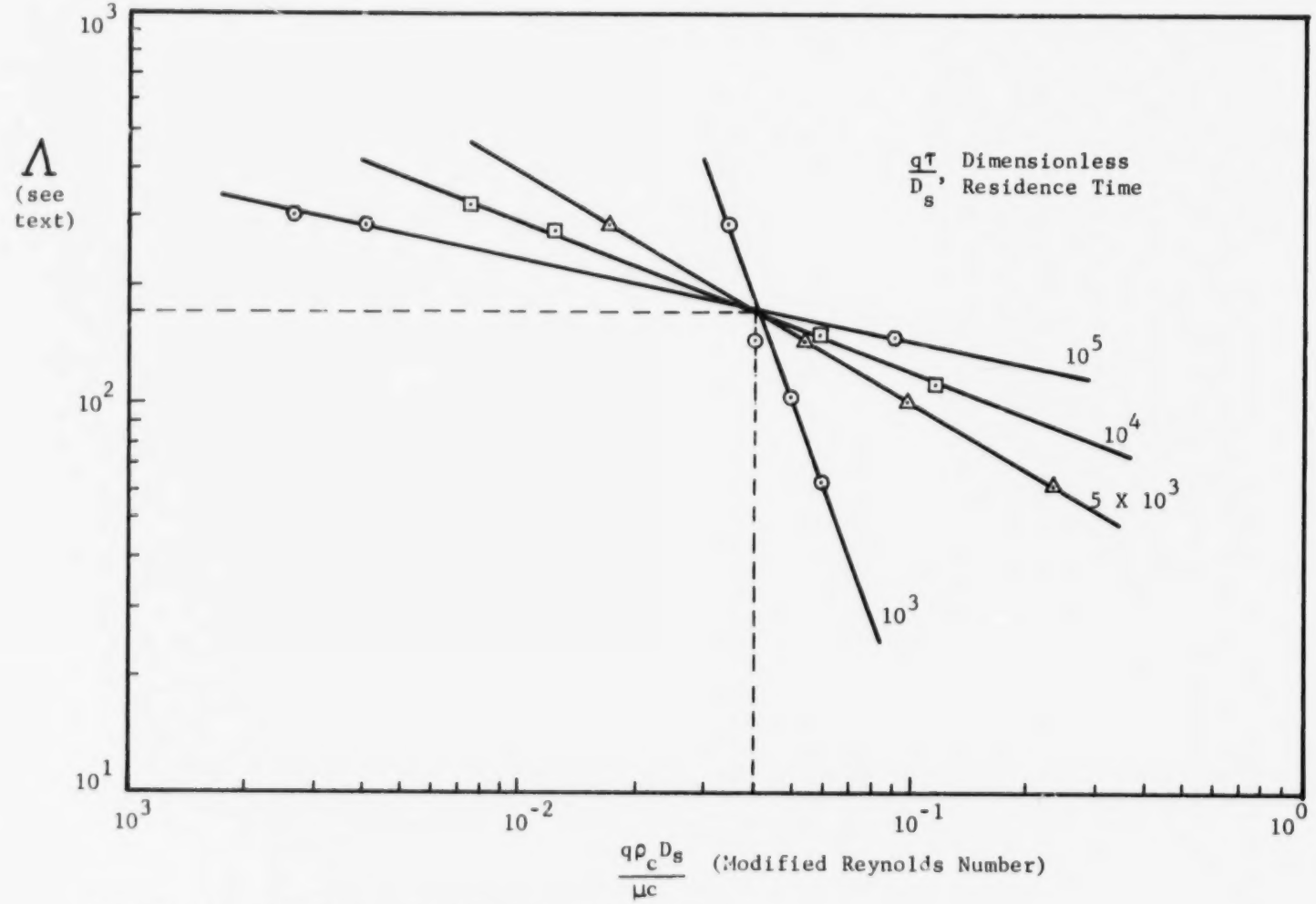


FIGURE 11: PERFORMANCE CURVES FOR SWINE WASTEWATER

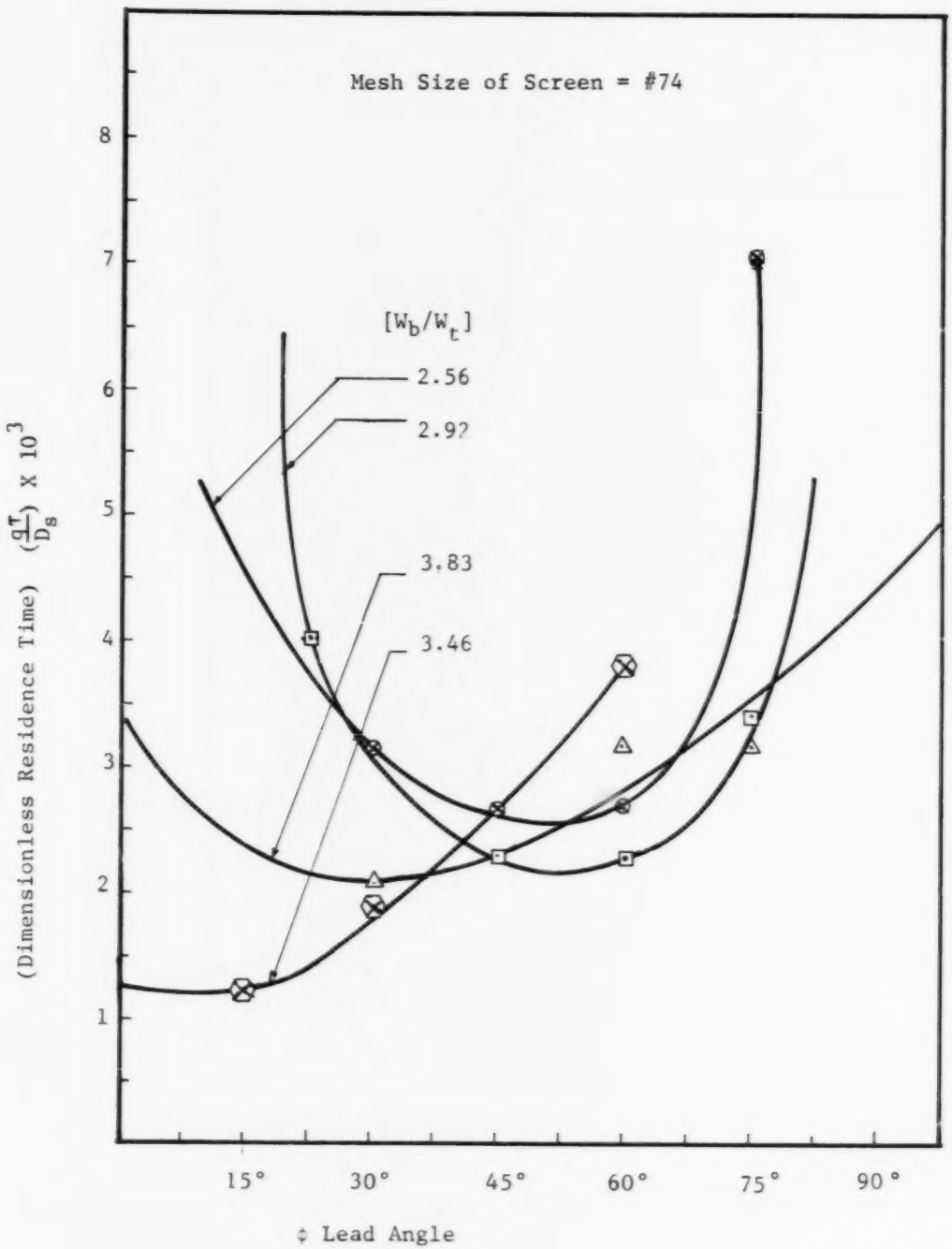


FIGURE 12: OPTIMIZATION PLOTS FOR BEEF CATTLE WASTEWATER

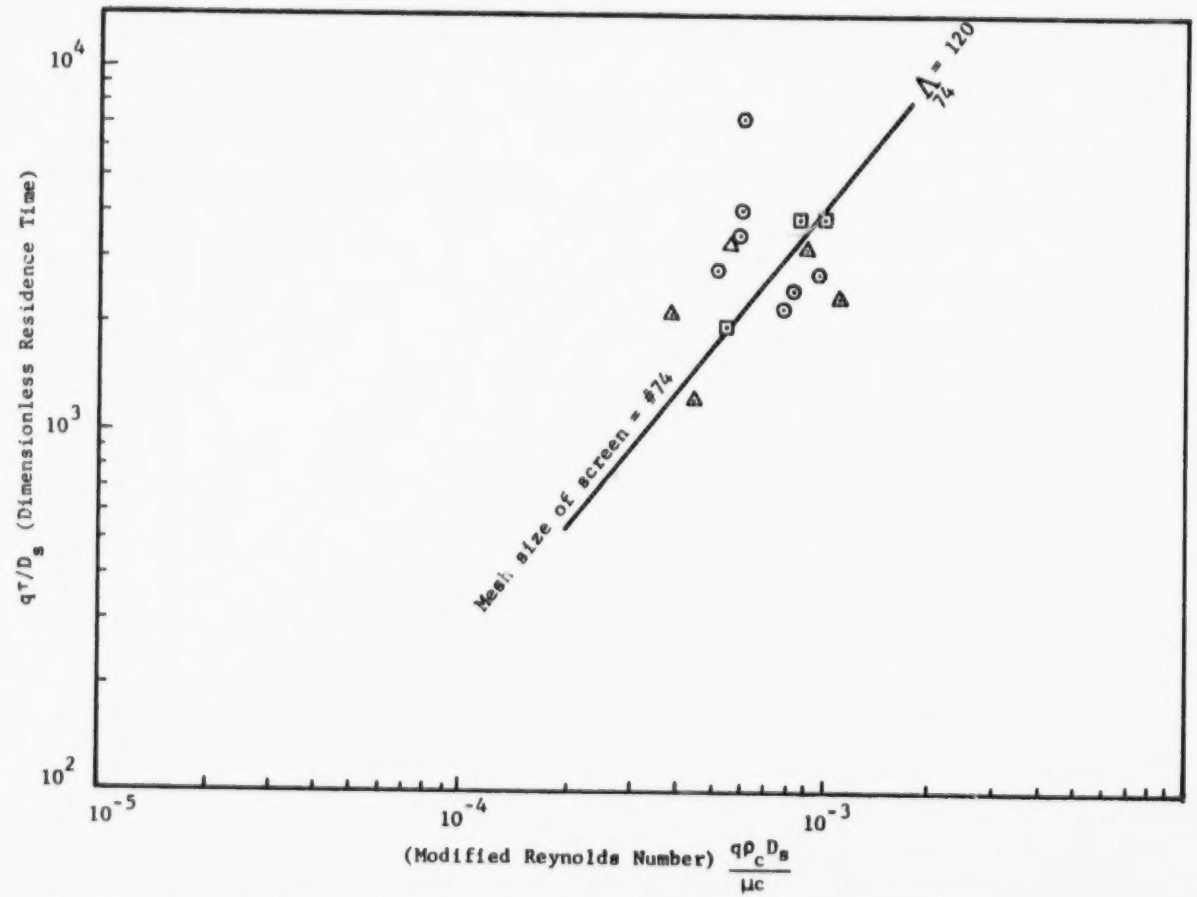


FIGURE 13: SCREEN PERFORMANCE CURVE FOR BEEF CATTLE WASTEWATER

the very preliminary stages of a sand filter study which was undertaken.

Sand Filter Experiments and Results:

In all, three sand filters were constructed and tested. The first two were made out of plastic tubes, each 5 ft long with 2-inch and 4-inch inside diameters respectively. The third sand filter was made out of treated plywood stock. The wooden column was made in 1-ft sections with a square cross-section of inside dimensions approximating 1 ft. The 1-ft sections can be bolted together to provide varying depths of sand column. The flow through a cross-sectional area of one square foot of the wooden column facilitated loading rate studies.

Figure 14 shows a typical section through the sand filters used. Each filter was tapped at 1-ft intervals. A close-up picture of the sand filter setup with sampling accessories is shown in Figure 15. The columns were packed with washed silica sand roughly sieved between screen mesh sizes #28 and #48.

The first concern of our investigation was to determine potential removal efficiencies obtainable from sand beds as a function of depth. Swine wastewater diluted 1:10 and 1:20 with tap water and previously sieved through a #60 mesh size of screen was filtered through 4 ft sand filters. The feed wastewater and samples collected at depths of 6", 1', 2', 3' and 4' were analyzed for total solids (TS), COD and total nitrogen. A summary of the results is given in Table 14.

Table 14 shows that removal efficiencies between 90 and 95 percent were obtained for total solids after the wastewater was filtered through 4 ft of sand. At the same depth, the COD was depleted 22 to 39%. The corresponding removal efficiencies at various other depths in the bed can be seen in the table. These removal efficiencies are, to say the least, impressive. Between the vibrating screen and sand filters, it is quite apparent that removal efficiencies approaching 99% were well within reach for the solids. This performance far exceeds what can be expected from commercial centrifuges, vacuum filters or sludge dewatering presses.

Having been convinced about the tremendous potential of sand filters, the next logical preoccupation was with the general management of such filters. Flow rate studies extending over 24-hour periods were conducted on the one-square-foot filter. A free head of 3 inches was maintained during the test. Flow through the filter was clocked at approximately 2-hour intervals. These measurements showed that within the first two hours flow rates approximating 2.5 gallons/min-ft^2 can be achieved. However, as time progressed the flow rate dropped because of plugging problems at the filter surface. At the end of 24 hours the average flow rate was 0.5 gallons/min-ft^2. If an average loading rate of 0.5 gallons/min-ft^2 were assumed as feasible over 24-hours periods of continuous operation, a livestock operation processing 15,000 gallons of wastewater per day would require a filter of cross-sectional area

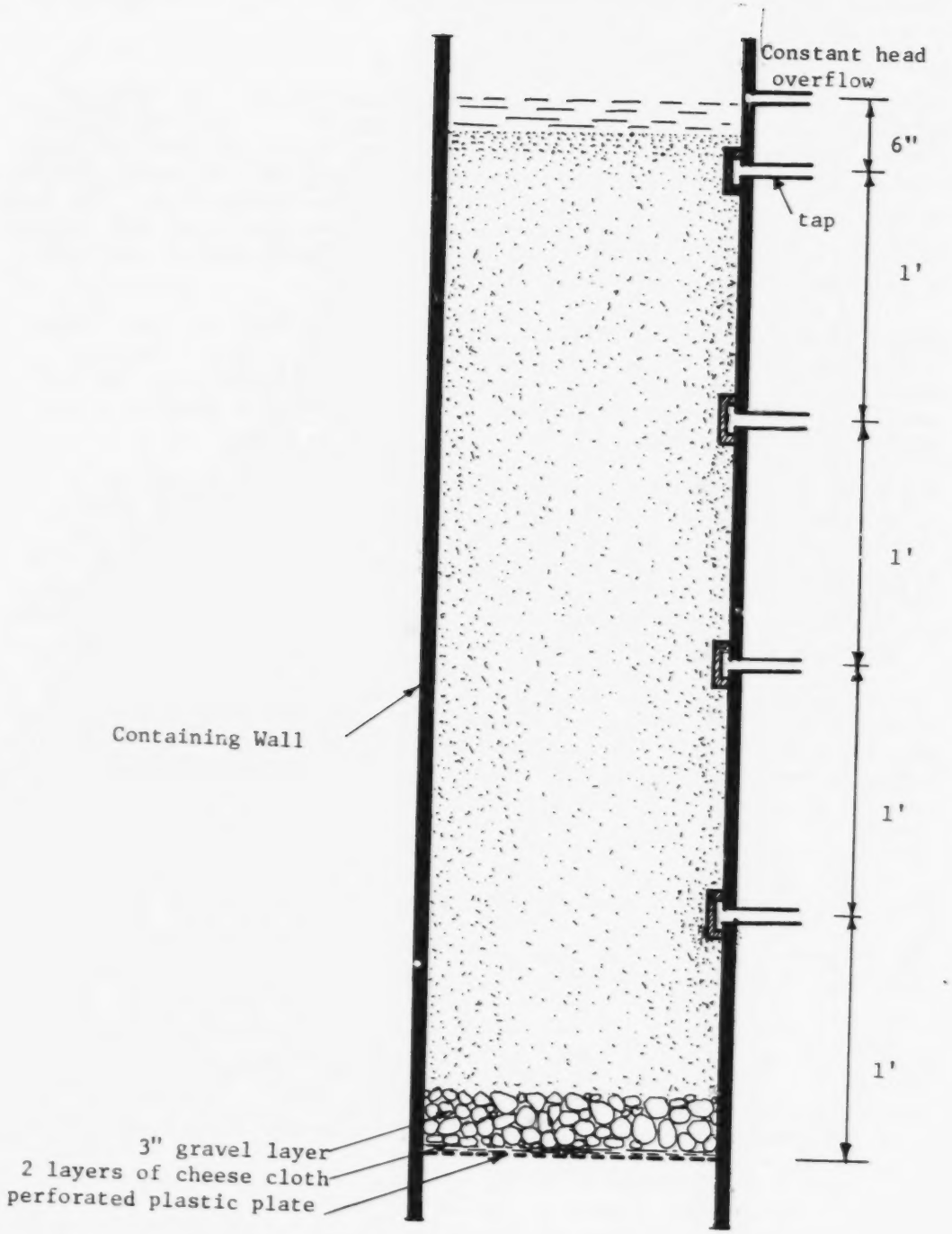


FIGURE 14: DIAGRAMATIC SECTION THROUGH EXPERIMENTAL SAND FILTER

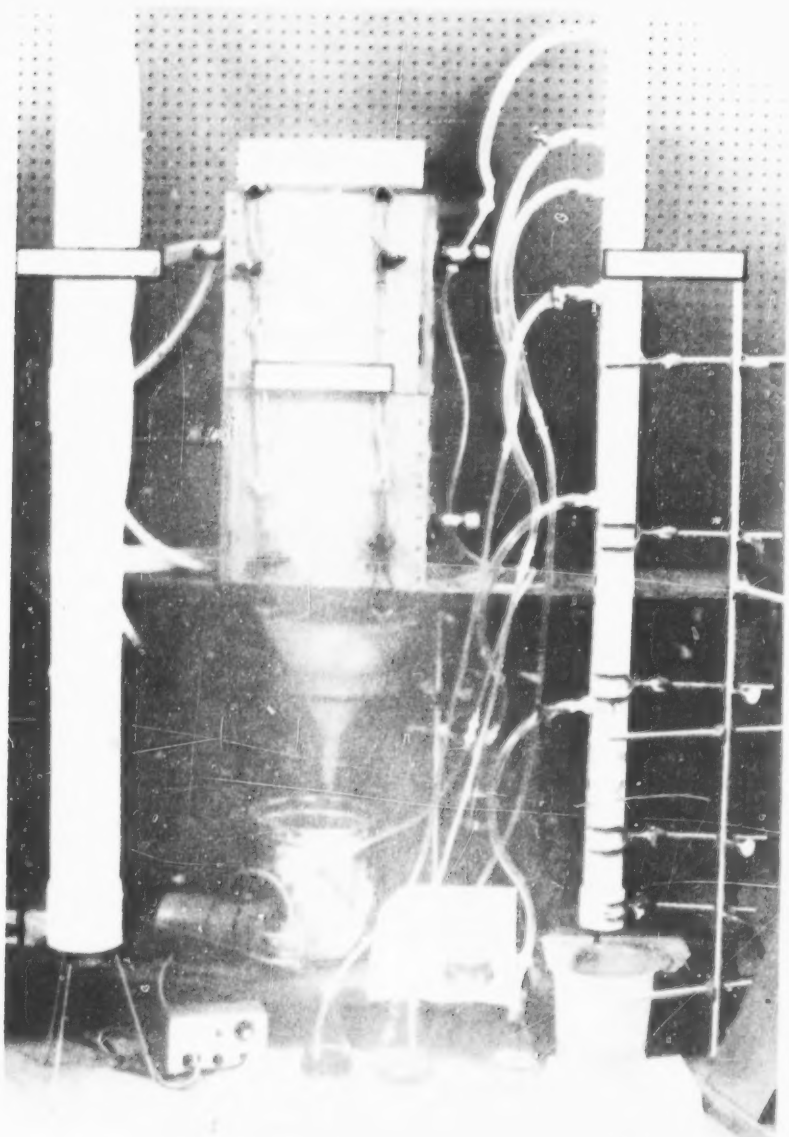


FIGURE 15: CLOSE-UP VIEW OF SETUP FOR SAND FILTER TEST

TABLE 14: SAND FILTER STUDY -- SWINE WASTEWATER

1:10 Dilution	Total Solids	% Change T.S. (-)	C.O.D. (PPM)	% Change C.O.D. (-)	Nitrogen (PPM)	% Change Nitrogen (-)
Original	.137%		4,260		717	
6" Filtered	.0538%	60.7%	3,200	24.8%	658	8.23%
1' Filtered	.0404%	70.5%	3,100	27.2%	658	8.23%
2' Filtered	.0252%	81.6%	2,920	31.45%	632	11.85%
3' Filtered	.0160%	88.3%	2,720	36.14%	624	12.97%
4' Filtered	.0142%	89.6%	2,590	39.2%	588	17.99%
1:20 Dilution						
Original	.0685%		1,960		340	
6" Filtered	.0082%		1,680	14.28%	322	5.29%
1' Filtered	.0164%	76.05%	1,560	20.4%	361	
2' Filtered	.0092%	86.56%	1,560	20.4%	330	2.94%
3' Filtered	.00613%	91.02%	1,560	20.4%	330	2.94%
4' Filtered	.00341%	95.0%	1,520	22.4%	248	27.05%

$$A = \frac{15{,}000 \text{ (gal./day)}}{24 \text{ (hrs/day)} \times 60 \text{ (min/hr)} \times 0.5 \text{ (gal./min-ft}^2\text{)}} = 21 \text{ square ft}$$

A sand filter 4 ft deep and of dimensions 5' X 5' (if square) or 6 ft diameter (if circular) would do the job. Since it will be necessary to scrape the top inch of the filter surface following each 24-hour period of continuous operation, it will be desirable to have two or more filters of this type so that daily cleaning would not be necessary.

Recommendations Regarding Sand Filtration of Livestock Wastewater:

From the limited experience we have had with sand filters at this stage, the following recommendations are in order:

(i) Coarse sand filters have a potential as a high efficiency remover of solids from livestock wastewater. It is essential that the wastewater be screened prior to application on the filter.

(ii) Flow rates of about 0.5 gpm/ft^2 of filter surface can be achieved over 24-hour periods of operation. It is essential to point out that the rate-of-flow measurements in this study were done on small filters in which wall effects constitute a significant impediment to flow. Higher flow rates are to be expected from larger filters.

(iii) Plug-up for fresh manure appears to be primarily restricted at the very top inch of the surface. If the solids are digested prior to filtration through the filter, they tend to penetrate much further into the bed.

(iv) Further intentive research of sand filters is needed before they can be considered a feasible proposition. Hydraulic studies and management studies directed at plug-up problems should be given first priority in such studies.

SECTION VI

CHARACTERISTICS OF THE COMPONENT LIQUID AND SOLID FRACTIONS OF BEEF CATTLE AND SWINE WASTEWATERS

Following the separation process on the vibrating screen, the solid and liquid fractions were analyzed for their physical, chemical and biological properties. The data obtained from these analyses are detailed in Tables 16a, b and c for swine wastewater and in Tables 17a, b and c for beef cattle wastewater.

The Solid Fraction:

The solid fraction as used here, implies that the waste slurry has been diluted 1:10 or more times for washing purposes and then screened through an appropriate mesh size of screen. The solids held back on the screen constitute the solids fraction.

In general these solids were found to be extremely fibrous. They had a moisture content ranging between 75-85% (wb). They were odorless and when exposed over extended periods of time, did not develop any fly larvae. On the basis of mere visual observations the solids seemed stable and easily storable. A summary of the essential properties of the solids are presented in Table 15. A number of the basic characteristics of these solids appear to be significant at first sight. The most eye-catching of these is probably the high volatile solids percentage of the solids in a muffle furnace confirmed the figure of about 91.5% TS shown in Table 15. The corresponding figure for beef cattle solids is 87.8% TS. Since these solids are mostly residues of the original feed which passed through the digestive tracts of the animal without being affected, it appears strange that they should be so high in volatile solids. Previous observations in biological treatment systems have shown that these types of solids are only very slowly biodegradable. The fundamental question is then why such supposedly biologically inert solids should be so high in volatile matter. The answer to this question is of course closely tied to the basic metabolic mechanism by which celluloses and lignins are hydrolyzed to soluble substrate in biological systems. At best, such processes, if favored at all, proceed at an extremely slow pace.

The C:N:P ratio as inferred from COD, nitrogen and phosphorus values in Table 15 appears to be favorable for some type of microbial action tending to promote putrefaction. Since the stability of the solids under conditions of extended storage is of primary interest in the overall study, an attempt was made to compost the fibrous solids in the mesophyllic-thermophilic temperature range so that the intensity of biological activity could be observed as an index of stability for the solids under storage.

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TABLE 15: SUMMARY SHEET CHARACTERISTICS OF THE SOLID FRACTION (SWINE AND BEEF CATTLE WASTEWATER)

	SWINE			BEEF CATTLE		
Total Solids (TS)	17-20%			10-15%		
Volatile Solids	91.5% TS			87.8% TS		
COD	249,450 ppm	1.41	grams / gram TS	162,350 ppm	1.64	grams / gram TS
Nitrogen (Total)	7,896	.045		3,868	.039	
Ca	6,700	.0067		3,000	.003	
Mg	5,500	.0055		2,500	.0025	
Zn	300	.0003		82	.000082	
Cu	5,270	.0053		5	.000005	
Fe	140	.00014		240	.00024	
Mn	49	.000049		12	.000012	
Na	1,150	.00115		200	.000200	
K	6,770	.00677		10,000	.01000	
P	39,500	.0395		16,000	.016000	

TABLE 16(a): SWINE WASTEWATER SCREENED

	Composite before Screening	Effluent from 60 Mesh	Effluent from 100 Mesh	Effluent from 200 Mesh	Effluent from 325 Mesh
Total Solids	8.3%	5.36%	5.08%	4.99%	4.79%
% Change (-)		33%	39%	40%	42%
Volatile Solids	82%	73.0%	73.5%	73.7%	73.3%
% Change		no	effective	change	
Nitrogen (ppm)	10,024	4,116	4,220	4,140	3,940
% Change		58.9%	57.9%	58.69%	60.6%
COD (ppm)	80,000	59,400	57,028	56,210	52,195
% Change (-)					
BOD (ppm)	36,000	19,800	18,600	18,300	18,000
% Change (-)					
Expressed as grams/gram of total solids					
Nitrogen	.1207	.07679	.08307	.08296	.08225
COD	.9638	1.1082	1.1225	1.1264	1.08966
BOD	.4337	.3694	.3661	.3667	.3757

TABLE 16(b): NUTRIENT AND MINERAL ANALYSIS OF SWINE WASTEWATER SOLID & LIQUID FRACTIONS

	Swine Composite (80% Urine + 20% Feces)	Screen Dried (60 Mesh)	60 Mesh Liquid 1:2 Dilution
Ca (ppm)	2,050	6,700	850
Mg (ppm)	1,000	5,500	475
Za (ppm)	40	300	18
Cu (ppm)	45	5,270	23
Fe (ppm)	50	140	20
Mn (ppm)	14	49	6
Na (ppm)	525	1,150	250
K (ppm)	2,900	6,770	1,440
P (ppm)	9,500	39,500	4,000
Expressed as Grams/Gram of total solids			
Ca	.024698	.006700	.015858
Mg	.012048	.005500	.0088619
Zn	.0004819	.000300	.000335
Cu	.0005421	.005270	.0004291
Fe	.0006024	.000140	.0003731
Mn	.000168	.000049	.0001119
Na	.006325	.001150	.004664
K	.034939	.006770	.0268656
P	.114457	.039500	.074627

TABLE 16(c): BIOLOGICAL OXYGEN DEMAND -- SWINE (80% URINE + 20% FECES) (NO DILUTION)

Days	* 325 Mesh (ppm)	* 60 Mesh (ppm)	** Composite (ppm)
0	0	0	0
1	10,000	18,000	10,000
2	16,000	21,000	15,000
3	22,000	26,000	25,000
4	31,000	31,000	31,000
5	32,000	30,000	37,000
6	37,000	30,000	38,000
7	39,000	28,000	37,000
8	41,000	34,000	37,000
9	42,000	29,000	37,000
10	43,000	27,000	37,000
11	43,000	26,000	37,000
12	43,000	32,000	39,000
13	44,000	36,000	38,000
14	43,000	38,000	38,000
15	43,000	32,000	38,000
16	43,000	28,000	37,000
17	43,000	24,000	37,000
18	43,000	24,000	35,000
19	43,000		
20	43,000		

* Effluent water from screen was analyzed for BOD

** Composite was analyzed for BOD prior to application on the screen

TABLE 17(a): BEEF CATTLE WASTEWATER SCREENED

	Composite before Screening	Effluent from 60 Mesh	Effluent from 100 Mesh	Effluent from 200 Mesh	Effluent from 325 Mesh
Total Solids	14.7%	6.38%	6.38%	6.072%	5.86%
% Change (-)	0	56.6%	56.6%	58.8%	60.3%
Volatile Solids	76.8%	78.5%	78.3%	77.3%	77.6%
% Change		no effective change			
Nitrogen (ppm)	8,650	8,425	8,340	8,230	7,920
% Change (-)		2.6%	3.56%	4.85%	8.439%
COD (ppm)	127,560	78,670	77,088	74,679	71,467
% Change (-)		38.3%	39.6%	41.5%	43.97%
BOD (ppm)	48,000	20,000	18,600	15,600	15,600
% Change (-)		57.5%	61.25%	67.25%	67.50%
Expressed as grams/gram of total solids					
Nitrogen	.05884	.1320	.1307	.1355	.1351
COD	.86775	1.23307	1.2082	1.2298	1.2195
BOD	.3265	.3197	.29153	.25691	.26621

TABLE 17 (b): NUTRIENT AND MINERAL ANALYSIS OF BEEF CATTLE WASTEWATER LIQUID & SOLID FRACTIONS

		Beef Cattle Composite (60% Feces + 40% Urine)	Screened Dried Solids (60 Mesh)	60 Mesh Liquid 1:2 Dilution
Ca	(ppm)	1,700	3,000	800
Mg	(ppm)	690	2,500	215
Zn	(ppm)	18	82	14
Cu	(ppm)	-----	5	22
Fe	(ppm)	122	240	30
Mn	(ppm)	16	12	6
Na	(ppm)	130	200	33
K	(ppm)	3,350	10,000	2,100
P	(ppm)	7,750	16,000	2,000
Expressed as Grams/Gram of total solids				
Ca		.011567	.003000	.012539
Mg		.004694	.002500	.003369
Zn		.0001224	.000082	.0002194
Cu		-------	.000005	.000348
Fe		.0008299	.000240	.0004702
Mn		.0001088	.000012	.000094
Na		.0008843	.000200	.0005172
K		.022789	.010000	.032915
P		.05272	.016000	.0313479

TABLE 17(c): BIOLOGICAL OXYGEN DEMAND -- BEEF CATTLE (60% FECES + 40% URINE) (NO DILUTION)

Days	* 325 Mesh (ppm)	* 60 Mesh (ppm)	** Composite (ppm)
0	0	0	0
1	5,500	12,000	20,000
2	12,000	13,000	28,000
3	16,000	18,000	36,000
4	17,500	23,000	44,000
5	19,500	28,000	48,000
6	21,000	29,000	49,000
7	22,500	28,000	49,000
8	25,000	28,000	54,000
9	28,000	28,000	50,000
10	29,500	27,000	49,000
11	29,500	26,000	48,000
12	31,000	28,000	55,000
13	31,000	27,000	56,000
14	31,000	27,000	58,000
15	31,000	27,000	53,000
16	31,000	26,000	49,000
17	31,000	26,000	43,000
18	31,000	26,000	43,000
19	31,000		
20	31,000		

* Effluent water from screen is anal ed for BOD

** Composite was analyzed for BOD prior to application on the screen

Compost Study on the Screened Solids:

A close-up view of the laboratory composters used in this study is shown in Figure 16. Approximately 4 cubic feet of each type of waste solids (swine and beef cattle) were composted. Prior to introduction into the reactors, the screened solids were squeezed manually to a moisture content of approximately 65%. The biological reactors were made of glass cylinders with rubber gasketed metal end plates. Air saturated with water vapor was introduced through the bottom of each reactor for aeration purposes. By saturating the air in this manner prior to introduction into the reactors, problems of dehydration associated with artificially aerated composts were held down to a minimum.

The head space gases of each reactor were exhausted through a tap on the head plate. The exhaust gases were bubbled through a barium hydroxide solution for carbon dioxide stripping. Copper-constantan thermocouples were placed at three locations (close to the bottom, at the middle and near the top) in each reactor. A multi-channel potentiometer regulated by a time clock provided hourly read-out of the temperature profile in each reactor. The whole apparatus was housed in a controlled temperature chamber which was maintained at 95°F throughout the compost period of 20 days.

In Figure 17, the recorded temperature profiles for each of the composts are shown. Following initial equilibration at the ambient temperature approximately 8 hours after the beginning of the experiment, the temperature at all positions in the reactors showed hardly any deviation from the room temperature. There was a maximum deviation of 5°F above this value on the second day, after which the temperature dropped to 95°F and never rose above it for the rest of the test period. Daily inspection of the barium hydroxide solution showed no visible precipitate of carbonate salts. Volatile solids determinations made at weekly intervals showed that there was practically no measurable dissipation of the volatile matter over a 20-day period.

The conclusion from these observations is that the solids are indeed reasonably stable and should store over extended periods without any odor nuisance or aesthetic problems. Under low temperature winter conditions the screened solids will store well on paved platforms beneath some type roof. Under warmer climatic conditions, the solids will dry readily under natural conditions to a fluffy, odorless, storable end product. It is envisaged at this point that these solids will ultimately be disposed of on the land. It seems logical that the winter stockpile can be spread comfortably during plowing operations the following spring.

For some time there has been a growing research interest in the recycling of manure solids as feed for livestock. Nutrient and mineral content of the screened solids suggest that they would be good candidates for feeding trials in a future study. An inspection of the comparative data in

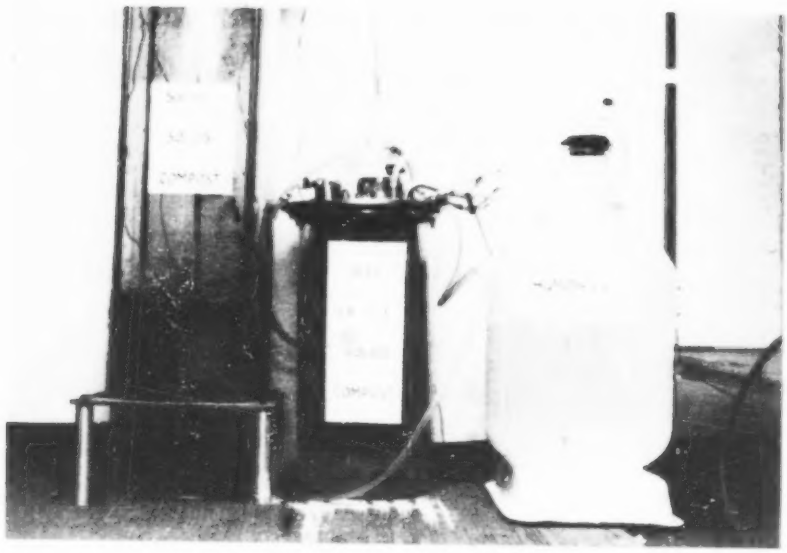

FIGURE 16: CLOSE-UP VIEW OF EXPERIMENTAL COMPOST SETUP.

Table 17b suggests that a substantial percentage of the minerals and nutrients in the original feed are still present in the screened waste solids. Of course, the availability of these nutrients can only be determined in experiments in which animal growth responses are systematically analyzed.

The Liquid Fraction:

The properties of the liquid fraction from the screen are detailed in Tables 16a, c and c for swine wastewater and in Tables 17a, c and c for beef cattle wastewater.

A significant reduction in resistant solids has taken place in the screening process. The solids still present in the liquid fraction are largely colloidal in nature and are expected to be the most biologically degradable fraction. When further diluted in wash and transport water (a dilution approximating 1:10 is considered reasonable for this purpose),

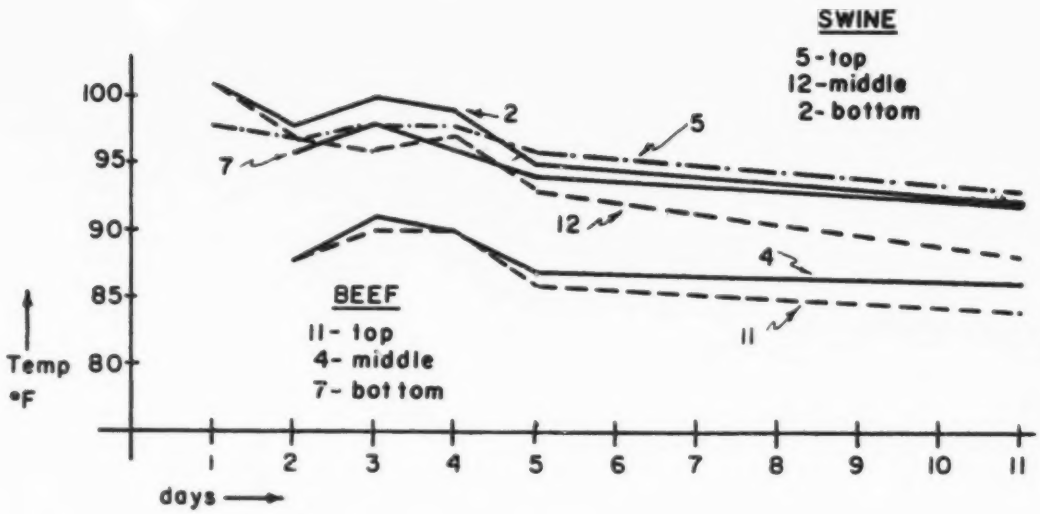

FIGURE 17: TEMPERATURE PROFILE OF COMPOST BEDS

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the total solids level of the wastewater from the screen would be below 0.5%.

A vast majority of the biological oxygen demand, minerals and nutrients is present in the liquid fraction. The liquids in all cases were odorous and had a pH of about 8.5 when fresh. Under anaerobic storage conditions these liquids will become a serious odor nuisance problem and would take up a sizable storage space. Treatability studies on the liquid fraction will be reported in the next section of the report. Along with these studies, we shall consider management strategies for beef cattle and swine wastewaters integrating treatment and recycling concepts to conserve both the gross quantity of water polluted as well as the size and cost of facilities required to meet mandatory winter storage specifications.

SECTION VII

COMPARATIVE BIOLOGICAL TREATABILITY STUDIES ON SWINE AND BEEF CATTLE WASTEWATER LIQUID FRACTIONS

The data reported in Section VI of this report show that in passing through the vibrating screen separator, the liquid fraction retains:

(a) for swine wastewater:

50-70% of the original volatile solids
50-60% of the original BOD
60-70% of the original COD
50-90% of the original nutrient and mineral contents.

(b) for beef cattle wastewater:

50-70% of the original volatile solids
50-60% of the original BOD
60-70% of the original COD
50-90% of the original nutrient and mineral contents.

The limited data on sand filtration presented in Section V of the report indicated that although a substantial proportion of the residual solids has been removed in the sand filter following initial screening, the BOD, COD, nutrient and mineral contents of the liquid fraction remain substantially potent as a potential pollutant and/or nuisance odor problem.

A large number of previous studies (2, 13, 14) has already established the fundamental treatability of animal wastewaters in aerobic, anaerobic or multi-stage biological systems. It is assumed that this basic property remains essentially unaltered in the liquid fraction following the isolation of resistant solids. From the detailed tabulation of the basic properties of the liquid fraction in Section VI there is no question that the residual (COD):(nitrogen):(PO_4-P) ratio far exceeds the minimum value of 100:5:1 specified for conventional biological treatment systems. In view of the recognized adverse effect of excessive solids on transport processes in such biological systems, it is hypothesized that the reduced solids level together with the associated reduction in BOD and COD concentrations would substantially enhance treatment kinetics of the liquid fraction. If such improvement can indeed be demonstrated, then a sound basis would have been established for either relaxing present design criteria or making such specifications substantially more effective.

In all, three types of treatments were studies, namely: strict anaerobic, aerobic and combined anaerobic-aerobic stabilization of the liquid fraction.

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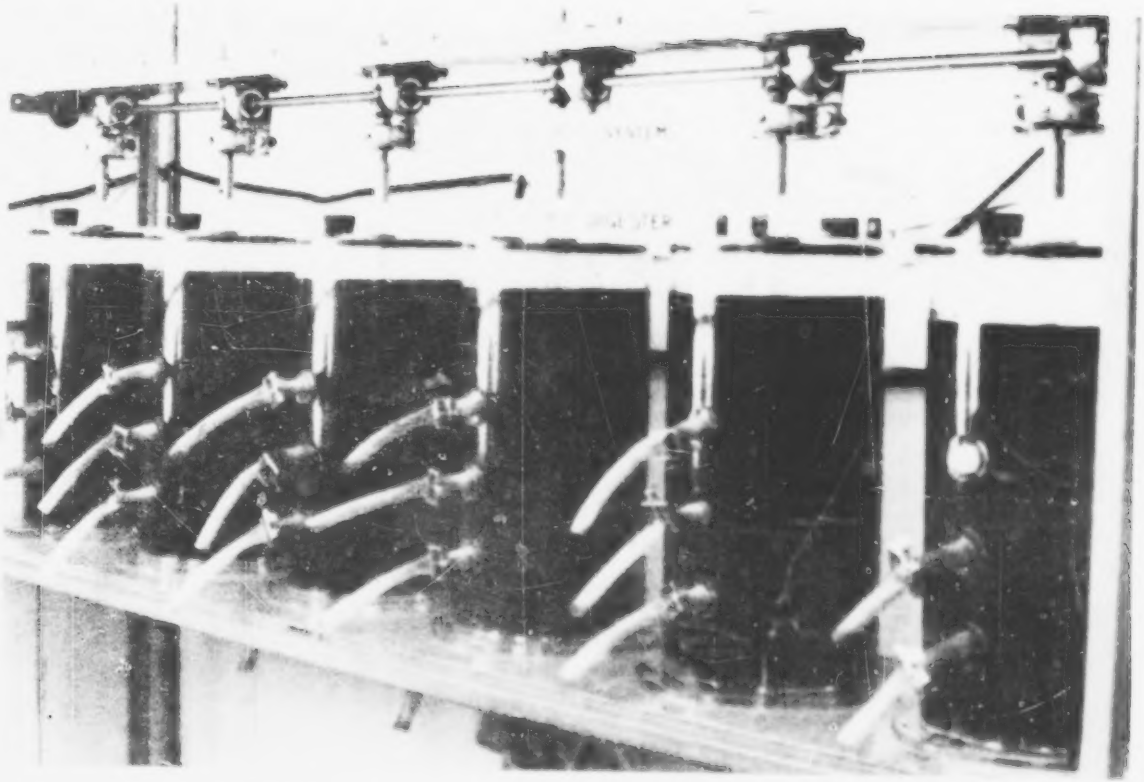

FIGURE 18: CLOSE-UP VIEW OF ANAEROBIC DIGESTERS

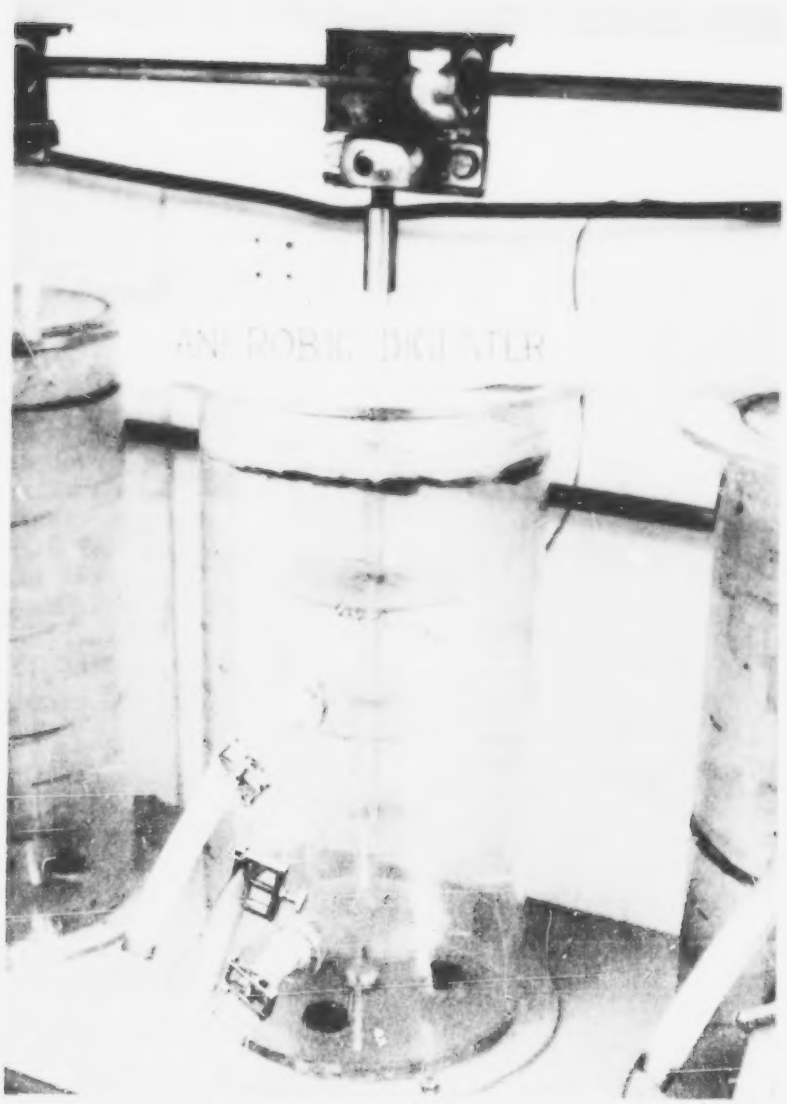

FIGURE 19: DETAIL OF ANAEROBIC DIGESTER

Anaerobic Digestion:

Experimental Apparatus: Six anaerobic digesters (Figure 18) were assembled for the study. Each digester had an operating capacity of 11 liters and was made of 8-inch diameter, 3/4-inch thick plexi-glass stock. A close-up view of a typical digester showing its salient features is presented in Figure 19. The chief components of the digester are:

(a) rubber-stoppered loading port and gas trap on the cover plate

(b) three sampling outlets on the side

(c) a baffled-impeller mixing assembly.

The system was constructed so that it was for all practical purposes air tight. Gases produced during fermentation could be collected if desired. The mixing impellers in all six digesters were operated by a common drive system consisting of a variable speed electric motor and six bevel gear arrangements driven by a main horizontal shaft. The rotational speed of the impellers could be varied between 0 and 500 rpm. The electric motor was operated on a percentage timer which allowed a 10-minute mixing interval every hour. The entire assembly was housed in an environmental walk-in chamber capable of controlling temperatures to within $\pm$ 1°F of the desired value. All digestion tests were performed at 95°F. All tests were run in duplicate.

Acclimation Procedure: An acclimation period of 15 days preceded the actual experimental runs. Each digester was seeded with a filtered mixed culture obtained from the bottom sludge of a functioning oxidation ditch at the Michigan State University swine farm. Each digester was operated until visible flocs began to form. Thereafter, the unit was settled daily for a period of 30 minutes, the supernatant liquid drawn off and the system refed with the prospective test sample. After the 15th day each digester had reached an impressive mixed liquor suspended solids level of between 2,000-4,000 mg/l. At this point the unit was considered ready to receive its first load of the test sample.

Experimental Procedure: This study was strictly carried out to determine the comparative merit of solids removal as it affects kinetic parameters in the digester. The digesters were operated for limited detention periods of between 10 and 15 days -- just long enough to see established kinetic patterns. The digesters were operated on a batch-fed, draw-and-fill basis. Mixed liquor volatile solids and COD were measured either daily or on alternate days as indices of digester performance. The pH was maintained in the range between 7 and 8 throughout the test period.

Experimental Results and Discussion: The data obtained from the anaerobic studies undertaken are summarized in Table 18 for swine wastewater liquid fraction and in Table 19 for beef cattle wastewater liquid fraction. The loading rates of the digesters are reported either as a dilution factor or in the more conventional manner of giving them as pounds

TABLE 18: ANAEROBIC DIGESTION OF SWINE WASTEWATER LIQUID FRACTION
Mesh Size of Screen = #60. Digestion Temperature = 95°F.

Dilution or Loading	Days	(%) Total Volatile Solids (TVS)	(%) Reduction in TVS	(ppm) COD Remaining	K (base 10) COD Removal Rate Constant	Predicted Detention Time for 50% COD Removal
	0	0.55	0.00	5,490		
	1	0.486	11.70	5,480		
	2	0.374	32.00	5,241		
	3	0.355	35.50	4,800		
1:5 =	4	0.327	40.60	4,409		
0.34	5	0.343	37.70	4,300	$\frac{(0.145)}{day}$	7 days
$(\frac{lb\ VS}{cfd})$	6	0.304	44.80	4,050		
	7	0.347	37.00	-----		
	8	0.343	37.70	3,600		
	9	0.341	38.00	-----		
	10	0.341	38.00	3,100		
	0	0.256	0.00	4,200		
	1	0.232	9.40	4,000		
	2	0.210	18.00	4,200		
	3	0.205	20.00	3,950		
	4	0.209	18.40	3,800		
1:10 =	5	0.201	21.50	3,900	$\frac{(.071)}{day}$	15 days
0.16	6	0.194	24.30	3,700		
$(\frac{lb\ VS}{cfd})$	7	0.203	20.80	3,700		
	8	0.210	18.00	-----		
	9	0.207	19.20	3,600		
	10	0.214	16.50	3,400		
	11	0.198	22.80	-----		
	12	0.218	14.90	-----		
	13	0.205	20.00	3,000		
	14	0.208	18.80	-----		
	15	0.201	21.50	2,600		
	0	0.185	0.00	1,497		
	1	0.181	2.20	-----		
	2	0.147	20.60	1,331		
	3	0.139	24.90	1,200		
	4	0.125	32.50	-----		
1:20 =	5	0.136	26.50	-----	$\frac{(.161)}{day}$	6.5 days
0.115	6	0.111	40.00	950		
$(\frac{lb\ VS}{cfd})$	7	0.124	33.00	-----		
	8	0.131	29.20	850		
	9	0.111	40.00	-----		
	10	0.132	28.70	-----		

TABLE 19: ANAEROBIC DIGESTION OF BEEF CATTLE WASTEWATER LIQUID FRACTION
Mesh Size of Screen = #60. Digestion Temperature = 95°F.

Dilution or Loading	Days	(%) Total Volatile Solids (TVS)	(%) Reduction in TVS	(ppm) COD Remaining	K (base 10) COD Removal Rate Constant	Predicted Detention Time for 50% COD Removal
	0	0.99	0.00	12,900		
	1	0.88	11.20	------		
	2	0.76	23.30	11,148		
	3	0.72	27.30	------		
	4	0.65	34.40	9,817		
1:5 =	5	0.66	33.40	------	$\frac{(0.087)}{day}$	12 days
0.61	6	0.615	37.90	10,040		
$(\frac{lb\ VS}{cfd})$	7	0.625	36.90	------		
	8	0.629	36.50	8,560		
	9	0.632	36.20	------		
	10	0.678	31.60	8,200		
	0	0.470	0.00	7,800		
	1	0.440	6.40	7,750		
	2	0.417	11.30	7,800		
	3	0.403	14.30	7,400		
	4	0.378	19.60	7,200		
	5	0.371	21.10	-----		
1:10 =	6	0.339	27.90	7,000	$\frac{(0.076)}{day}$	14 days
0.3	7	0.342	27.30	-----		
$(\frac{lb\ VS}{cfd})$	8	0.345	26.60	6,400		
	9	0.326	30.70	6,600		
	10	0.344	26.90	6,400		
	11	0.308	34.50	-----		
	12	0.315	33.00	-----		
	13	0.309	34.30	6,000		
	14	0.310	34.10	-----		
	15	0.305	35.20	5,000		
	0	0.264	0.00	2,912		
	1	0.260	1.60	-----		
	2	0.238	9.90	2,682		
	3	0.222	16.00	-----		
	4	0.209	18.90	-----		
1:20 =	5	0.210	18.50	2,590	$\frac{(0.087)}{day}$	12 days
.165	6	0.185	30.00	-----		
$(\frac{lb\ VS}{cfd})$	7	0.245	-----	2,175		
	8	0.200	24.30	-----		
	9	0.199	24.70	2,270		
	10	0.216	18.20	-----		

of volatile solids per cubic foot of digester per day. Within the broad context of this study, the dilution method is convenient since we are ultimately interested in the management of waste slurries subjected to a mandatory dilution in wash and transport water.

Semi-log plots of the COD removal data in Figure 20 furnishes us with approximate COD removal rate constants for the anaerobic tests. These constants are tabulated as K (base 10) in Tables 18 and 19. Since the plots of Figure 20 approximate a first order kinetic pattern, we can assume the following metabolic equation to apply:

$$E = KT/(1 + KT) \qquad (4\text{-}1)$$

where E = COD removal efficiency

K = COD removal rate constant (1/day)

T = detention time (in days)

Equation 4-1 is easily rearranged to the form:

$$T = E/K(1 - E) \qquad (4\text{-}2)$$

Using equation 4-2 we can now estimate expected detention periods necessary to achieve 50% COD removal from the various digester operating conditions. The calculated values are recorded in Tables 18 and 19. For swine wastewater liquid fraction diluted 1:20 or else loaded into the digester at the rate of 0.115 (lb.VS/cfd), we need approximately 7 days to dissipate 50% of the initial COD. The characterization data in sections IV, V and VI suggest a COD/BOD ratio of between 2 and 4 for swine wastewater liquid fractions. It is therefore safe to conclude that a 50% COD reduction is equivalent to BOD reduction far in excess of the 90% level. The implication of this now becomes that 7 days of anaerobic digestion of the liquid fraction under the operating conditions specified would eliminate over 90% of biological oxygen demand. Under similar loading and operating conditions (but without solids separation), Taiganides (14) reports that a minimum detention period of 10 days would be required for comparable treatment of hog wastes in an anaerobic digester. It appears therefore that considerable improvement in treatment kinetics can be achieved by solid separation processes preceding anaerobic digestion.

Although the experiment was set up to simulate high rate anaerobic digesters, the results are expected to be no less true for anaerobic lagoons subject to varying ambient temperature conditions. The performance of such lagoons can be considerably improved by sensible removal of resistant solids prior to charging the lagoons. Present design specifications of such lagoons have not met the nuisance odor problem adequately. Solids separation could help to improve lagoon performance to a point where odors can be further suppressed.

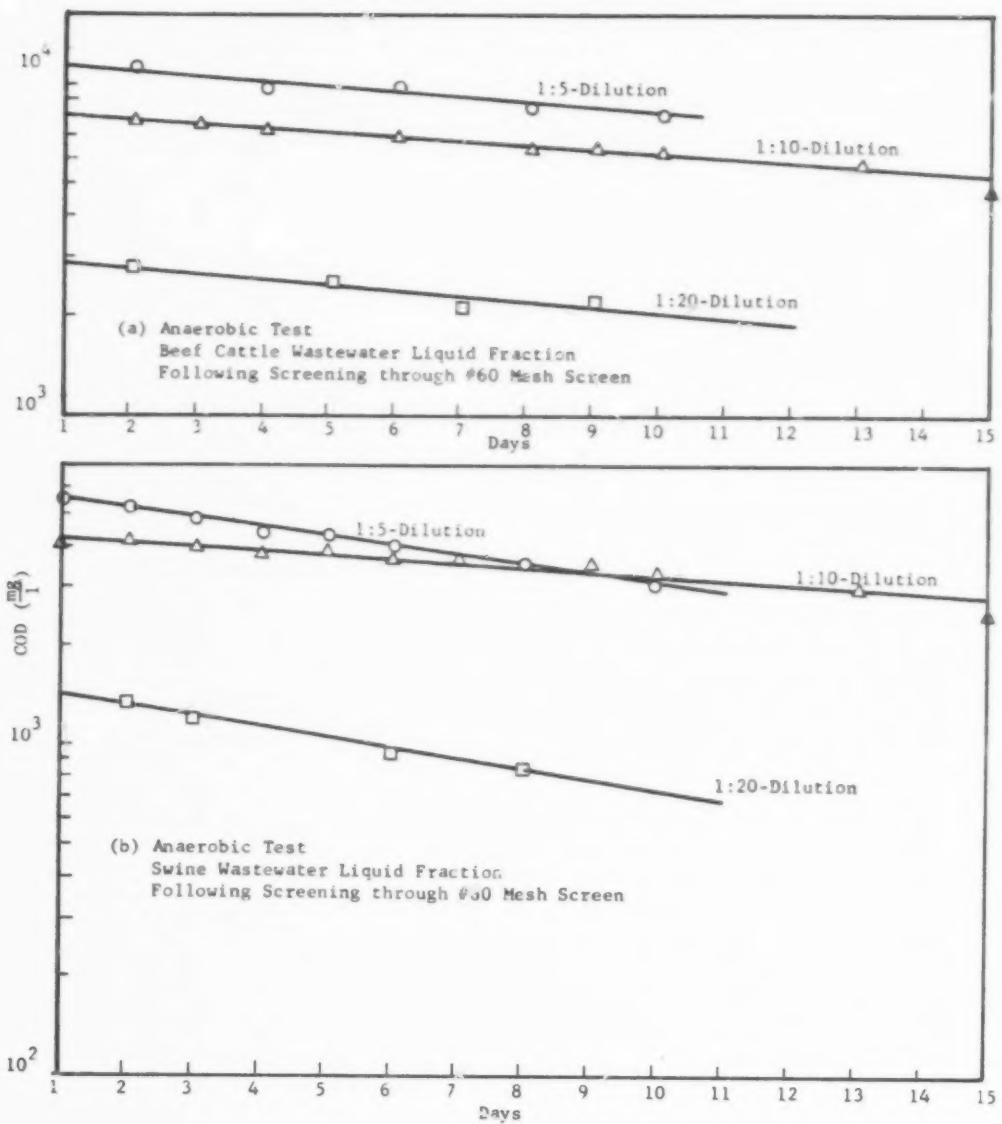

FIGURE 20: ANAEROBIC DIGESTER PERFORMANCE PLOTS

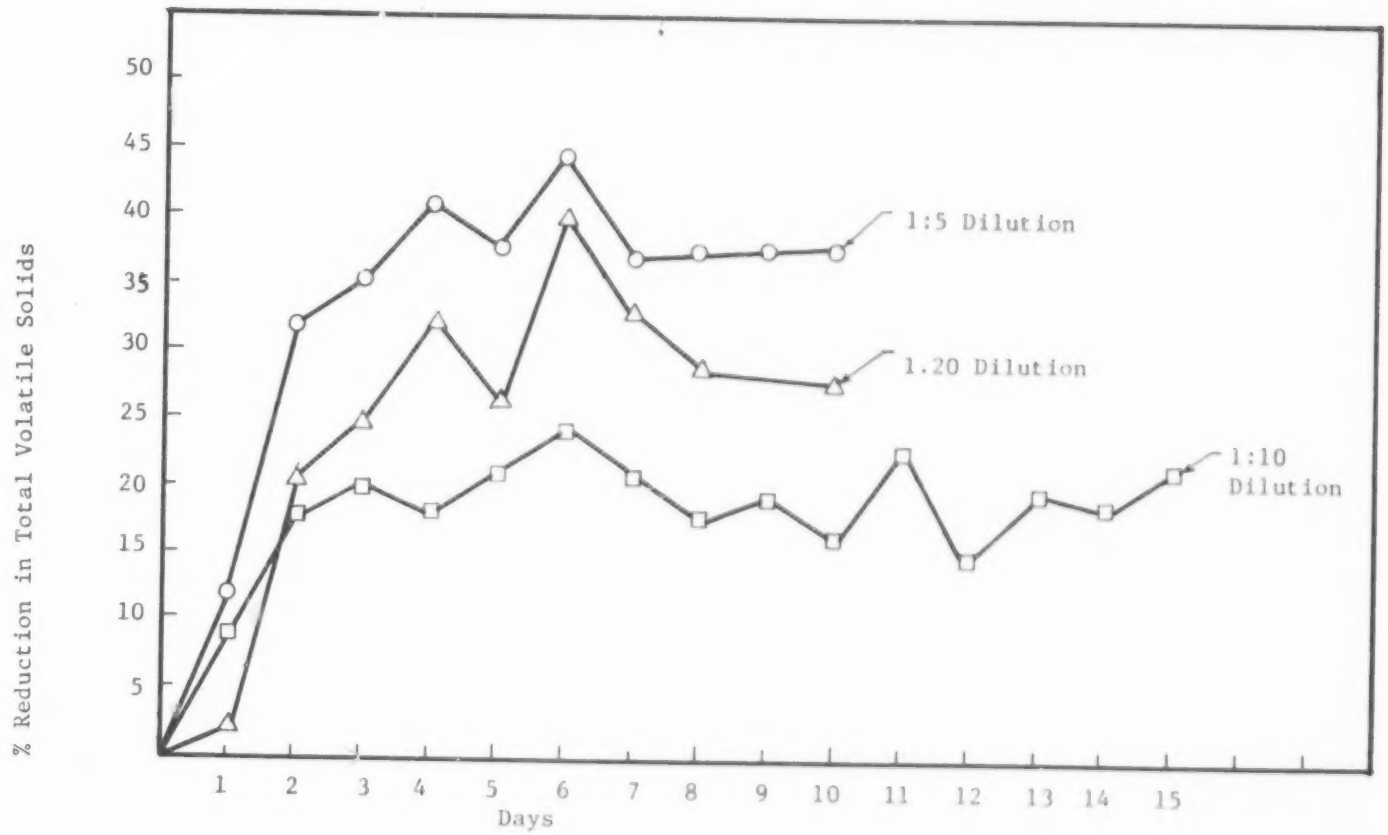

FIGURE 21: VOLATILE SOLIDS DISSIPATION FOR SWINE WASTEWATER ANAEROBICALLY DIGESTED AT 95°F

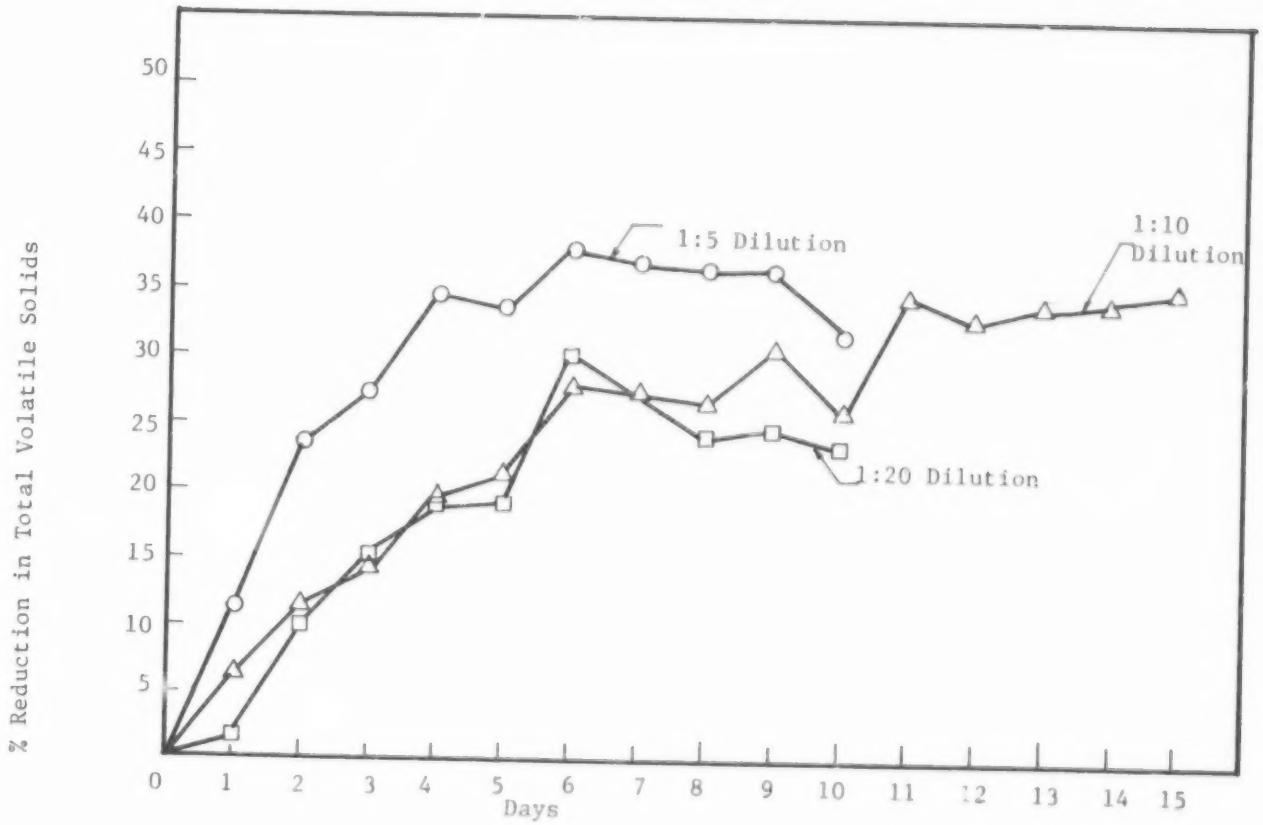

FIGURE 22: VOLATILE SOLIDS DISSIPATION FOR BEEF CATTLE WASTEWATER ANAEROBICALLY DIGESTED AT 95°F

In the short interval of the test, considerable dissipation of volatile solids was obtained. Figures 21 and 22 show the percentage reduction in volatile solids as a function of time. The general unsteady behavior of the solids is typical of the mixed liquor and reflects the complex dynamics of growth, synthesis and dissipation of volatile solids occurring simultaneously in these systems. This characteristic pattern serves as additional evidence that the digesters were operating satisfactorily. In the absence of more generally accepted behavior indices such as total volatile organic acids and alkalinity, the total volatile solids performed a very essential service.

Aerobic Digestion Tests:

Experimental Apparatus: The bioxidation system together with some of the instrumentation used is shown in Figure 23. The basic system consists of four batch-fed, fill-and-draw type units equipped with porous stone diffusers for aeration purposes. Each unit had an operating capacity of 8 liters. Enough air was forced through the diffusers to provide adequate mixing while maintaining dissolved oxygen levels no less than 2 ppm throughout the test period.

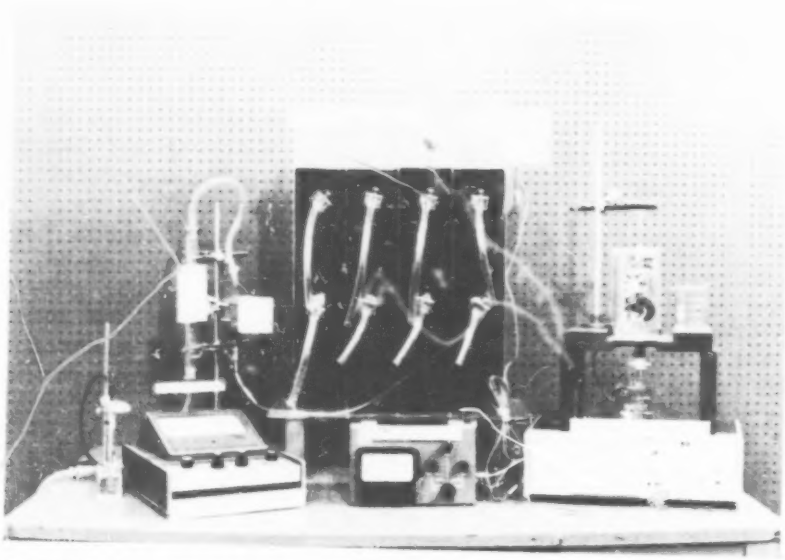

FIGURE 23: CLOSE-UP VIEW OF BIOXIDATION APPARATUS

Acclimation Procedure: A procedure similar to the one previously described for the anaerobic tests was used. Each bioxidation unit was seeded with a filtered mixed culture taken from the effluent of an operating oxidation ditch on the Michigan State University swine farm. The unit was then aerated until visible flocs were formed. On each subsequent day thereafter, the system was settled for 30 minutes, decanted carefully, refed and aerated. This process continued until a mixed liquor suspended solids level of about 6000 mg/l was reached. At this point the unit was considered ready to receive the first load of test sample. Again the acclimation period was 15 days.

Experimental Procedure: The bioxidation units were fed once a day on a draw-and-fill basis. The detention time on the average test was 10 days. However, the test was discontinued whenever sufficient data had been obtained to estimate the removal rate constant. Most of this type of data was obtained between 6 and 8 days.

Two basic types of raw sample were used, namely:

(a) screened only or screened and sand filtered prior to bioxidation and

(b) screened and anaerobically pretreated prior to bioxidation.

In each test the pH was maintained between 7 and 8. Daily COD measurements were made as the primary performance index. The operating temperature of the digesters was about 70-75°F.

Experimental Results and Discussion: The data obtained from bioxidation tests on swine wastewater liquid fraction are summarized in Table 20. Kinetic plots of this data are presented in Figure 24. Similar representations of the experimental data on beef cattle wastewater can be seen in Table 21 and Figure 25.

The removal rate constants for COD are particularly impressive. In the treatment of municipal wastewaters by extended aeration in aerated lagoons it is customary to use estimates of K in the range 0.55 to 1.0 per day for cases in which the removal rate constant has not been explicitly determined. Compared with the above value, K values ranging between 0.4 and 0.8 per day obtained in the various tests reported here are indeed impressive. The removal of resistant solids from the mixed liquor substantially improves transport processes such as oxygen transfer and substrate diffusion. The absence of these solids also effectively reduces the viscosity of the liquor which is directly related to mixing operations in the biological reactor.

It is interesting to note that sand filtration following the initial screening step does not seem to improve the removal rate constant in both cases tested. This would suggest that additional solids removal in a sand filter may be superfluous.

TABLE 20: AEROBIC DIGESTION OF SWINE WASTEWATER LIQUID FRACTION

Dilution	Days	(1) Screened on #60 Mesh Prior to Bioxidation C.O.D. (ppm)	(2) Screened on #60 Mesh + Sand Filtered (4ft) Prior to Bioxidation C.O.D. (ppm)	(3) Screened on #60 Mesh Anaerobically Digested for 10-days Prior to Bioxidation C.O.D. (ppm)
1:10	0	1,081	1,000	
	1	900	-----	
	2	750	700	
	3	600	-----	
	4	600	500	
	5	400	-----	
	6	395	340	
	7	398	-----	
	8	---	300	
	9	---	-----	
	10	---	-----	
1:20	0			871
	1			620
	2			442
	3			340
	4			240
	5			150
	6			169
	7			---
	8			---
	9			---
	10			225

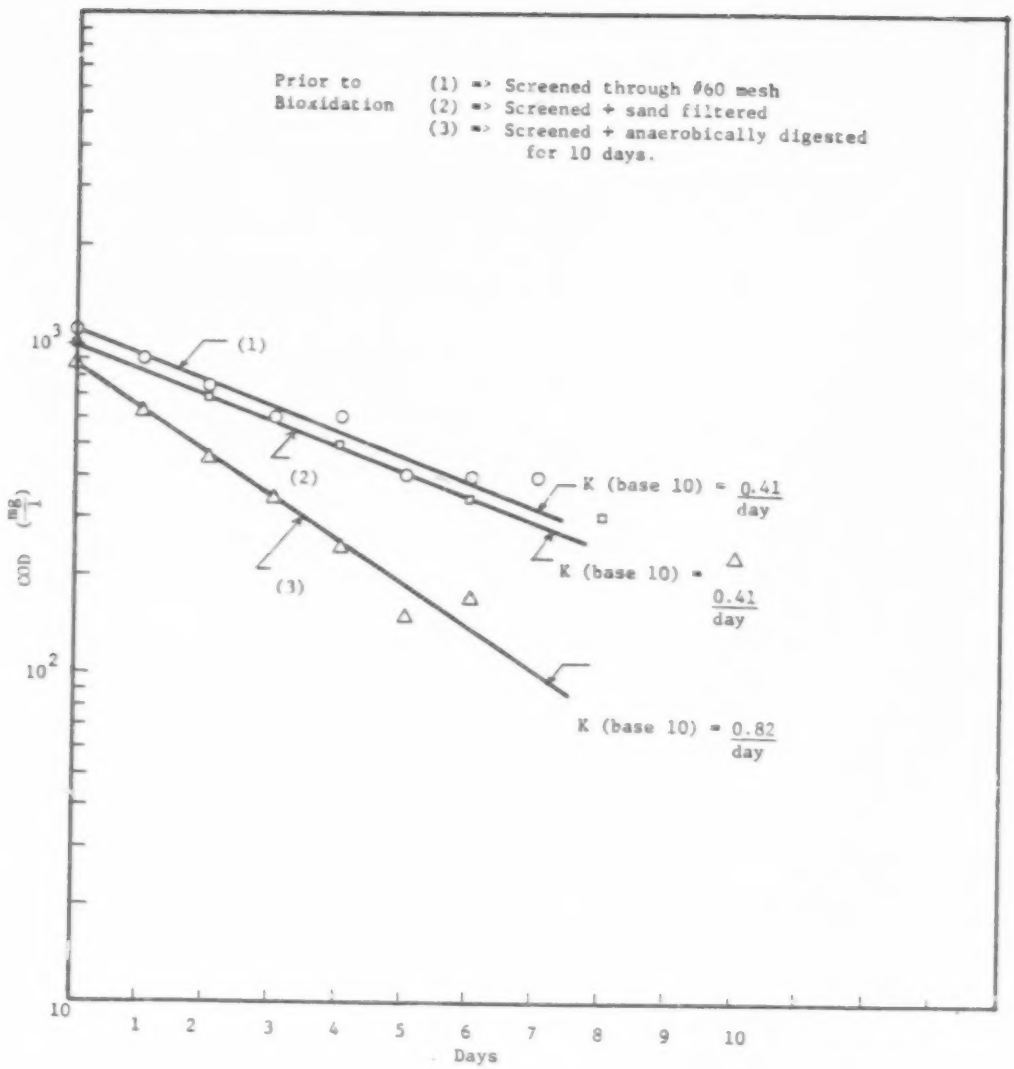

FIGURE 24: BIOXIDATION OF SWINE WASTEWATER LIQUID FRACTION, COD REMOVAL RATE PLOT

TABLE 21: AEROBIC DIGESTION OF BEEF CATTLE WASTEWATER LIQUID FRACTION

Dilution	Days	(1) Screened on #60 Mesh Prior to Bioxidation	(2) Screened on #60 Mesh + Sand Filtered (4 ft) Prior to Bioxidation
		C.O.D. (ppm)	C.O.D. (ppm)
	0	1,415	1,303
	1	1,100	1,000
	2	866	808
	3	600	650
	4	540	500
1:20	5	480	400
	6	320	320
	7	---	---
	8	---	320
	9	320	---
	10	---	---

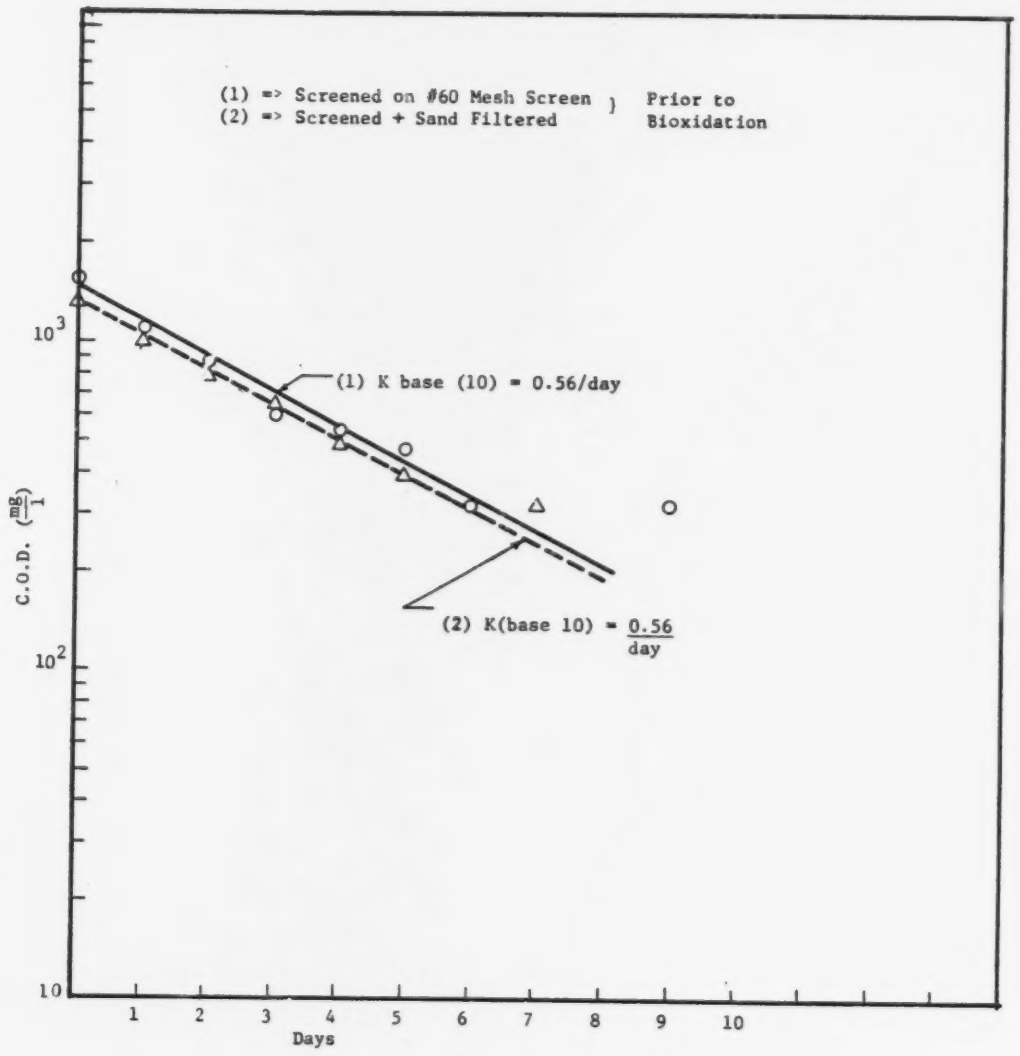

FIGURE 25: BIOXIDATION OF BEEF CATTLE WASTEWATER LIQUID FRACTION, COD REMOVAL RATE PLOT

Anaerobic digestion prior to bioxidation of the screened swine wastewater liquid fraction shows a very definite improvement in the oxidation kinetics. The removal rate constant was effectively doubled (see Figure 24). This is not at all surprising. An increasing amount of experimental evidence is being brought to bear on the fact that combined anaerobic-aerobic treatment systems are both functionally and economically best suited for managing highly polluted wastewaters such as concern us in this study. Biochemical theory of anaerobic metabolism appears to favor the combined process since the organic intermediates of anaerobiosis make easily available and usable energy sources for the aerobic culture. A synergism develops in which insoluble, otherwise unavailable waste organics are first hydrolyzed in the anaerobic step and then totally oxidized in the terminal bioxidation step.

SECTION VIII

DESIGN ALTERNATIVES

The primary object in this section is an attempt to provide design alternatives derived from integrating the salient features of this study into existing design concepts.

As a problem, we specify a Michigan hog producer raising an average of 1,000 market weight (150 lbs) animals at any time. This producer would process between 2,000 and 3,000 (say 2,500) hogs through his operation annually. It is our purpose to provide alternative designs to meet the following criteria.

1. In-the-building operation with automatic hydraulic collection and transport of wastes.

2. Provide odor-free storage for a minimum of 6 months over the winter period. When ultimately spread on the land following storage, there should be no odor-nuisance or pollution problems.

3. Employ concepts of treatment and recycle to minimize costs, conserve space and limit the gross bulk of water polluted.

4. Recommended waste characteristics as summarized from this and preceding studies are as follows:

(i) BOD_5 = 2.1 lb/1,000 lb of hogs

(ii) Manure production rate = 1.5 gallons per animal per day

(iii) Assume that in the process of collection and transport the manure is diluted 1:20 times.

Design #1: Aerated Lagoon with Diffused Aeration System

The basic system layout proposed can be seen in Figure 26. Its primary features are:

(i) In-building automatic flushing system.

(ii) Vibrating screen separator which takes out refractory solids prior to lagooning of the liquid fraction.

(iii) A control (inlet-outlet) structure. This structure should be housed in a metal shed large enough to contain an air compressor and the vibrating screen separator. Heat discharge from the compressor would keep the structure warm enough during winter to prevent freezing in subzero weather.

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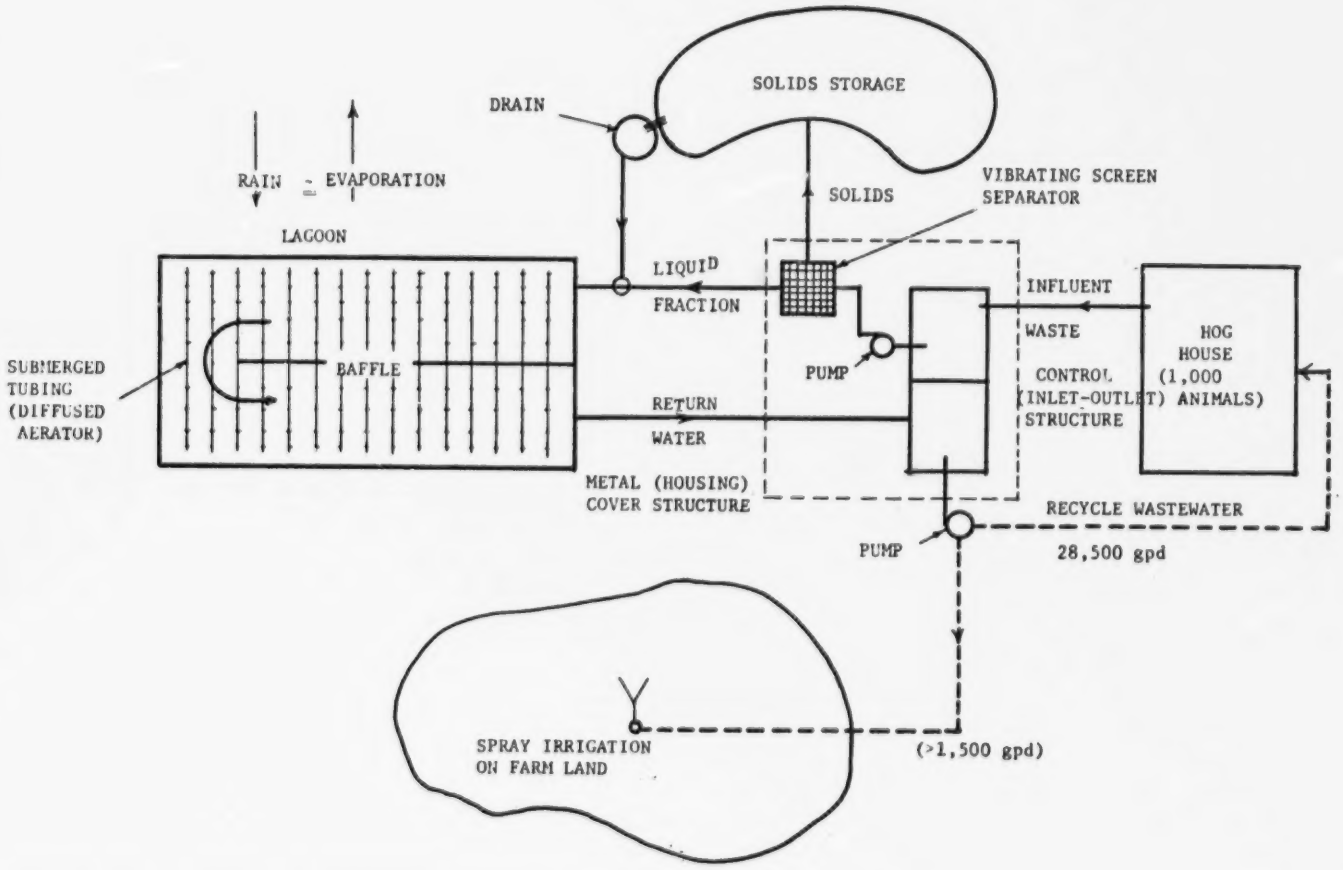


FIGURE 26: LAYOUT OF PROPOSED WASTE MANAGEMENT SYSTEM

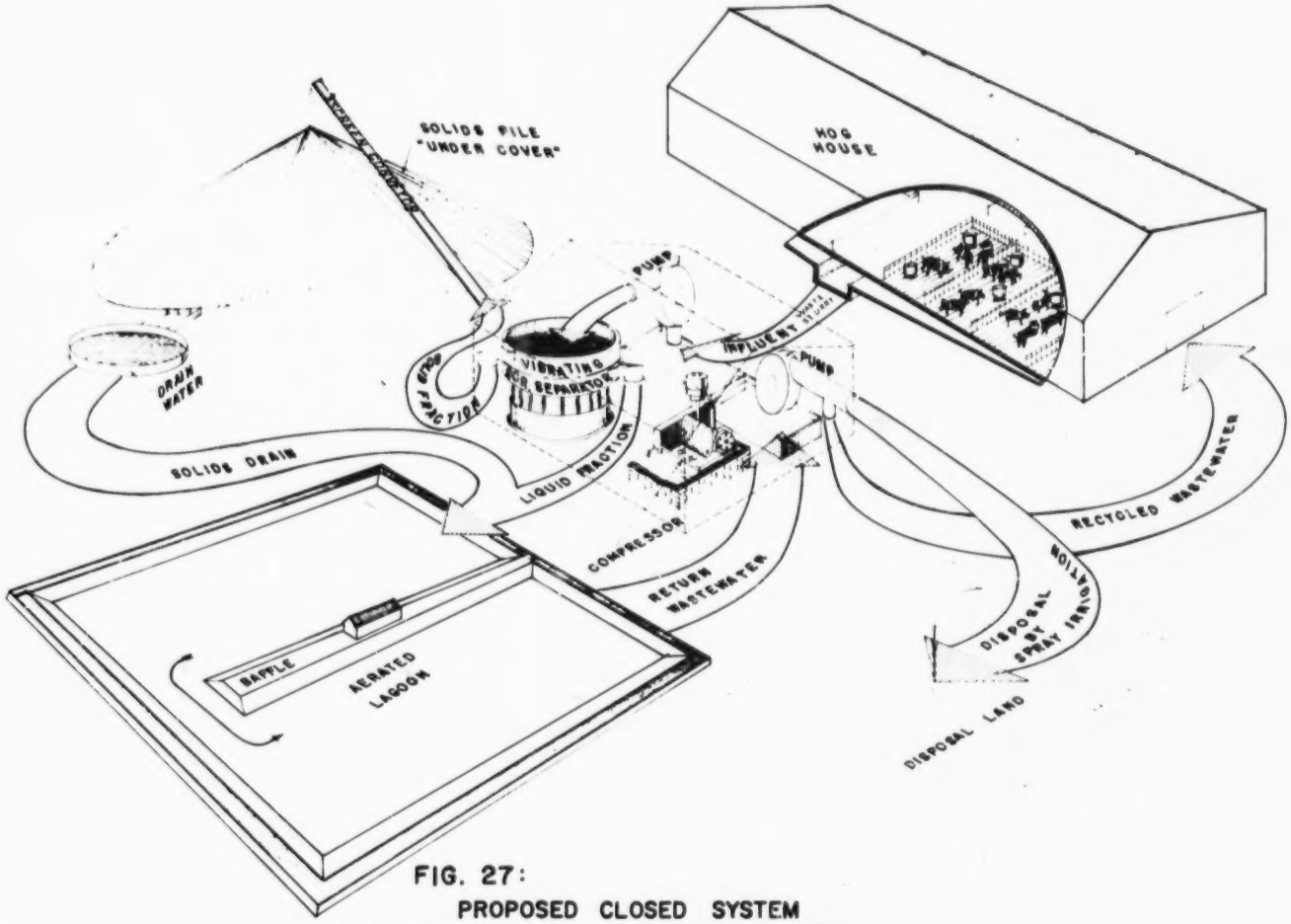


FIG. 27:
PROPOSED CLOSED SYSTEM
WASTE MANAGEMENT FOR LIVESTOCK

(iv) An aerated lagoon equipped with a diffused aeration system consisting of submerged perforated plastic laterals branching from metallic main pipes connected to an air compressor. A unique feature of the lagoon is that it is baffled to prevent short circuiting.

(v) Pumps and connecting pipe lines.

(vi) A solid storage space under snow cover draining into the lagoon and equipped for self loading and unloading.

(vii) Equipment (portable spray irrigation) for soil disposal of the lagoon effluent under favorable weather conditions.

The best-known manufacturer of the diffused aeration system proposed above is Hinde Engineering Company, 654 Deerfield Road, Highland Park, Illinois 60035. The system has the advantage that aeration continues undisturbed even in sub-zero weather when the lagoon surface is frozen. It is thus possible to operate the system on a recycling scheme all the year around.

Design Outline:

1. Estimated Organic Load: We assume a 50% reduction in BOD of raw waste following separation on the screen (see Section VI of the report for supporting data).

$$\text{Organic Load} = 1000 \text{ hogs} \times \frac{150 \text{ lbs}}{\text{hog}} \times \frac{(1.05 \text{ lbs } BOD_5)}{1000 \text{ lbs of hog}}$$

$$= 158 \text{ lb } BOD_5 \text{ per day}$$

2. Hydraulic Load: 1000 hogs at 1.5 gpd/hog = 1500 gpd of waste slurry. This will be diluted 20:1 by recycled water during transport. Assume no spray irrigation during the six winter months. Then

$$\text{storage for 6 months} = 6 \text{ (months)} \times 30 \frac{\text{days}}{\text{month}} \times 1500 \text{ gpd}$$

$$= 270{,}000 \text{ gallons} = 36{,}200 \text{ cubic feet}$$

3. Pond Specifications: Estimated organic load = 158 lb of BOD_5/day. Assume required removal = 90% => 142 lb of BOD_5/day.

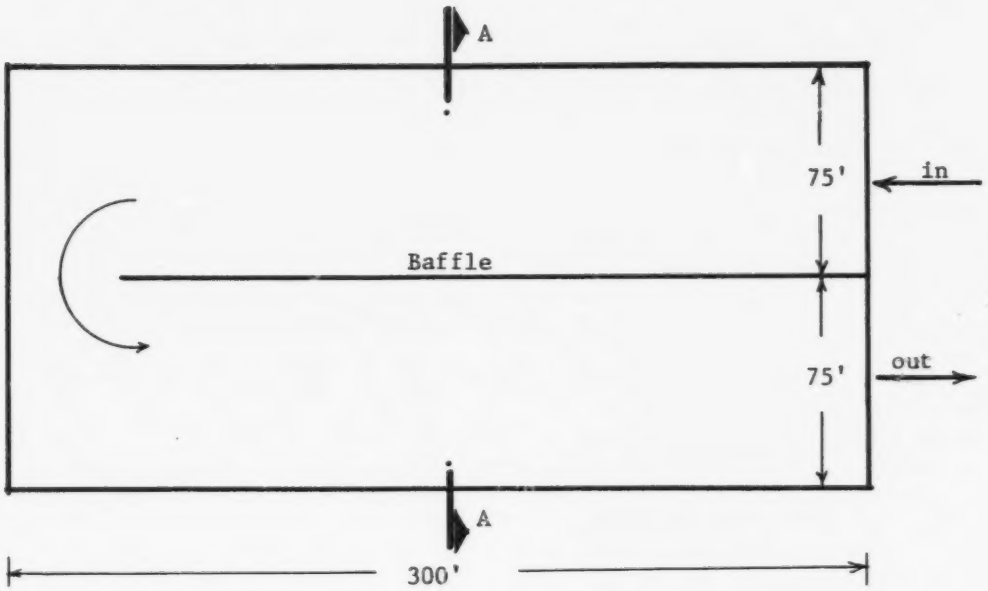
Allow 150 lb of BOD_5/acre -- 10 ft water depth (from Hinde Company Design Handbook).

$$\text{Area required} = \frac{158}{150} \simeq 1.0 \text{ acre or } 43{,}560 \text{ square feet.}$$

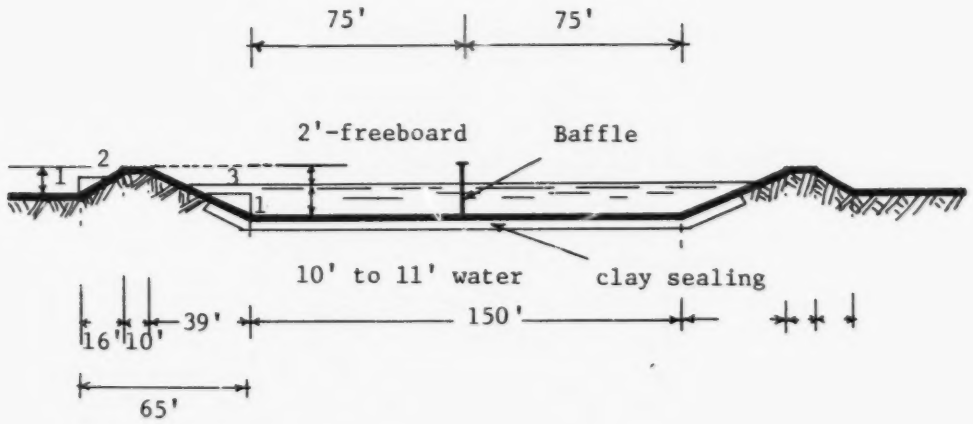
$$\text{Volume of pond} = 150' \times 300' \times 10'$$

$$= 450{,}000 \text{ cubic feet}$$

$$= 3{,}380{,}000 \text{ gallons}$$



(a) Top View of Lagoon



(b) Vertical Cross-section

FIGURE 28: LAGOON SECTION -- DETAILS

Detention at 30,000 gpd = $\frac{3,380,000}{30,000} \simeq 110$ days

4. Pond Construction: See Figure 28 for construction details.

Storage depth required = $\frac{36,200 \text{ ft}^3}{43,560 \text{ ft}^2} \simeq 1$ ft

i.e., over 6 months, pond depth increases from 10 ft to 11 ft.

5. Operation of Lagoon System: The start-up should be planned to coincide with good temperature conditions -- preferably summer or spring. The start-up procedure should include microbial seeding of the lagoon with about 5% of its volume of active return sludge from a properly functioning activated sludge system or extended aeration facility.

The lagoon should be filled with tap water to approximately the 10-ft depth mark as part of the start-up operation. Since the lagoon is designed for a 100-day detention period, discharge should be withheld for the first 100 days following initial input of wastes into the lagoon. Subsequently, spring, summer and fall discharges from the lagoon through a portable sprinkler irrigation system should average no less than 1,500 gpd to prepare the lagoon for storage of influent wastewater during the following winter.

It has been assumed that in Michigan and parts of the midwest region evaporative losses from the lagoon closely approximate rain water gains. This is generally true over a one-year period. For certain parts of the year, however, evaporative losses from the lagoon would be so high as to create a need for supplementary fresh water.

The solids stored over the winter months should be spread on the land the following spring. During favorable weather, accumulation of the solids over extended periods should depend on the availability of storage space. Our laboratory determinations show that the solids have a bulk density of 60 lb per cubic foot following screening. If 100% of the solids were taken out on the screen, assuming that the fresh manure contains 10% total solids then, over a 6-month period, a unit such as the one under consideration should provide space for solids storage of approximately:

$$\frac{1.5 \text{ gallons}}{(\text{hog})(\text{day})} \times 1000 \text{ hogs} \times \frac{30 \text{ days}}{\text{month}} \times 6 \text{ months} \times \frac{8.34 \text{ lbs}}{\text{gallon}} \times (0.1) \times \frac{1 \text{ ft}^3}{60 \text{ lb}_m} \simeq 4000 \text{ cubic feet}$$

A storage house 20' X 20' X 10' high would do the job. Since the actual percentage of solids removed by the screen on the average is only half of our design value, the storage space provided would be adequate for year around storage and should therefore allow for considerable flexibility in the management of solids disposal.

Under warm summer and spring conditions the solids would dry quite readily if exposed. Solids dried down to 10% moisture content (wet basis) were found to have a bulk density of about 20 lb per cubic foot. If it is intended to store this type of solid, a space three times that previously recommended would be necessary.

Since the handling of this amount of solids would require considerable manpower, it is advisable to mechanize the transport of the solids from the screen to storage and also the unloading of the solids from storage.

Construction Cost:

Assume good soil on the site and clay to seal the lagoon bottom on site.

1. Lagoon --

   (a) Strip site -- $200.00

   (b) Dikes -- 18 $\left(\frac{yd^3}{\text{linear ft}}\right)$ X (1,232 ft) $\left(\frac{\$0.4}{yd^3}\right)$ = $8,900

   (c) Baffle -- 300' at $6/ft = $1,800

   (d) Grass seeding = $1,000

   (e) Clay seal = $1,000

   (f) Piping (in and out) = $1,000

   (g) Aeration equipment:

Compressor, Tubings, etc.	= 10,000	
Labor to install	= 2,000	
Subtotal		$25,900

2. Pumping Station

(a)	Sump (sludge) pump	$ 500
(b)	Recycle and Spray irrigation pump	250
(c)	Control structure	1,000
(d)	Metal building over control structure	200
(e)	Electrical supply	300

	Subtotal		2,250
3.	Solids Separation System		
	(a) Vibrating screen separator	1,500	
	(b) Solids storage	500	
	(c) Solids handling equipment	500	
	Subtotal		2,500
4.	Automatic Flushing Equipment	3,000	
	Subtotal		3,000
		Gross total	$33,650

If we assume a five year amortization period, with 2500 animals being processed through the facility each year, then the investment costs in the system would be equivalent to $3 per hog excluding interest rate if money were borrowed to build the system. This amount of money may seem prohibitive at first sight, but compared with a winter underground storage tank costing $20,000, this would be a wise investment over the long run.

Design #2: Aerated Lagoon with Floating Surface Aerator

By using a floating aerator instead of the diffused system of Design #1, we can substantially reduce the cost of the aeration component. The major disadvantage of this alternative is that winter operation of the aerator is uncertain. To be safe, the design of a system using floating aerators should consider the lagoon as an inactive storage system during the six winter months. A six-month period of inactivity in the lagoon would have serious implications in the basic system design. It would mean that:

(a) recycling of lagoon water cannot be practiced during winter or in early spring just following lagoon thaw.

(b) the aeration equipment would be substantially overdesigned to handle the heavy oxygen requirement which must be satisfied immediately following the spring thaw to prevent the persistence of nuisance odors from the lagoon over the first few weeks of spring. A modified design is presented as follows:

1. Estimated Organic Load: from previous calculation this was found to be 158 lb of BOD_5 per day.

2. Hydraulic Load: 1000 hogs at 1.5 gpd/hog = 1500 gpd of slurry. This will be diluted 20:1 with fresh water during 6 months of winter storage when recycling of wastewater is impracticable.

$$\text{Storage for 6 months of winter} = 6 \text{ (months)} \times \frac{30 \text{ days}}{\text{month}} \times 30{,}000 \text{ gpd}$$

$$= 540{,}000 \text{ gallons} = 72{,}400 \text{ ft}^3$$

3. Pond Specifications: Assume mean BOD removal rate constant (K) of 0.1 per day. (From our bioxidation tests on the liquid fraction, this is quite conservative.) The required lagoon detention time is calculated from the pseudo-first-order equation:

$$E = KT/(1 + KT)$$

$$\text{or } T = E/(1-E)K$$

K = removal rate constant (per day)

T = detention time (days)

E = efficiency of removal

For 90% BOD removal

$$T = \frac{E}{(1-E)\ K} = \frac{.9}{(.1)(.1)} = 90 \text{ days}$$

At the peak period just following the spring thaw we must satisfy approximately 2 X (158 lb of BOD_5 per day) = 316 lb of BOD_5 per day.

Surface area of pond = 1 acre or 43,560 square feet (assumed)

Water depth = 10 ft (assumed)

Volume of pond = 150' X 300' X 10' = 450,000 cubic feet
= 3,380,000 gallons

Actual detention at 30,000 gpd = 110 days.

4. Aeration Equipment: Let D = Applied 5-day BOD in lbs/hr

L = Ratio of ultimate BOD to 5-day BOD (assume 1.47)

P = % BOD reduction

NOR = Normal (biological) oxygen requirement in lbs of oxygen per hour

then: $NOR = L \times D \times P = 1.47 \times \frac{316}{24} \times 0.9 \cong 17.5$ lbs of O_2 per hour for our system. Two 5-hp surface aerators with standard oxygen transfer rate of 3 lbs of O_2/hp-hr will be satisfactory for oxygenation and mixing requirements.

5. Lagoon Construction and Operation: This item would be identical to that for the previous lagoon, except that in winter no recycle from the lagoon is planned.

Construction Costs: These would be identical to the previous lagoon except that the floating aerators would cost approximately $3000 per unit and installation costs would be considerably less. In all, our estimate is that floating aerators would lead to savings of at least $5000 from the original estimate.

Operating costs for the floating aerators would be considerably less since they would be off all winter. Also in cases of malfunction, the surface aerators are more easily accessible and do not require any extraneous maintenance. The diffused aeration system in contrast, must be flushed twice a year with dilute hydrochloric acid and would be difficult to get at in cases of malfunction.

Other Designs: There are a number of other possible systems which can be developed from some of the completed or on-going research studies in livestock waste disposal, which would in effect, combine the essential features of the systems proposed.

Taiganides and White (15) of the Ohio State University are currently performing a demonstration study on a system which separates the refractory solids on a stationary screen. The liquid fraction is reclaimed in an oxidation ditch and then recycled for the collection and transport of influent hog wastes. The solid fraction is stabilized in a wet oxidation tank. The tank is integrated into the system in such a way that heat recovered from the wet oxidation process is used to maintain the temperature of the oxidation ditch under winter temperature conditions. This system has been in operation for less than two months (at the time this report was written). It is therefore too early to evaluate its performance. However, it is the type of bold and resourceful deviation from conventional practice which is likely to provide new directions in livestock waste management.

At Iowa State University, Smith, Hazen and Miner (16) are looking at two approaches to recycling of renovated wastewater for hogs involving:

(a) direct bioxidation of fresh hog wastewater in an oxidation ditch and

(b) sequential treatment of the hog wastewater in an anaerobic lagoon followed by an oxidation ditch prior to reuse.

This study together with an earlier study by Smith and Jenkins (17) indicates that excessive salt build-up would not be an acute problem in the operation of treatment systems designed on a recycling concept.

Experimental studies of an aerated lagoon system with spray irrigated effluent has been carried out by Dale et al. (18) at Purdue University.

The results of this study show that aerated lagoon effluents are odorless and can be resourcefully and conveniently disposed-of by sprinkler irrigation on farm land.

All of these studies show a very definite promise of radical new designs which would match the social and economic challenges of livestock waste disposal.

SECTION IX

ACKNOWLEDGEMENTS

Dr. B. A. Stout, Professor and Chairman, Department of Agricultural Engineering is gratefully acknowledged for carrying a major portion of the administrative burden and providing inspiration to the project to the very end.

The invaluable support of Mr. J. B. Barrows, President-Manager of Industrial Equipment Company of Detroit, Michigan, is acknowledged with sincere gratitude. Mr. Barrows furnished a Sweco Vibrating Screen Separator at no expense to the project for as long as was necessary to complete the test program.

In the early stages of its development, the following people provided administrative guidance to the project: Dr. M. L. Esmay, Professor, Department of Agricultural Engineering, and Dr. C. W. Hall, formerly Professor and Chairman, Department of Agricultural Engineering, Michigan State University and presently Dean of the College of Engineering, Washington State University, Pullman, Washington. The assistance of these individuals is gratefully acknowledged.

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SECTION X

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10 Author(s)

Ngoddy, Patrick O.
Harper, Jerome P.
Collins, Robert K.
Wells, Grant D.
Heidar, Farouk A.

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27 Abstract

The vibrating screen separator is examined for liquid-solid separation of livestock wastewater. A general procedure for performance analysis and estimation of this type of dewatering apparatus is developed and verified using methods of dimensional analysis. Tests on swine and beef cattle wastewaters show that the resistant or slowly biodegradable solids are effectively removed on vibrating screens ranging in mesh size from #60 to #120. Although it is measurably less efficient than conventional dewatering devices such as centrifuges and vacuum filters, the gravity dewatering screen separator is better suited to the economic scale of the average livestock operation.

The separated solid fraction from the screen is fibrous, odor free, stable, storable and does not attract flies. The absence of these solids from the liquid fraction is shown to stimulate faster rates of COD and nuisance odor dissipation presumably by enhancing otherwise rate-limiting transport processes in biological treatment systems.

The salient aspects of this study are integrated into candidate confinement livestock waste management designs.

Abstractor	Institution
D. Anderson	EPA/ORM

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